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REPRINT SERIES, Vol. XI

CONTRIBUTIONS FROM THE PSYCHOLOGICAL LABORATORY

BRYN MAWR, PENNA.

June, 1916

BRYN MAWR COLLEGE MONOGRAPHS

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PREFACE

From the standpoint of the worker in the subject the object of a volume of this kind is to collect under one cover from sources more or less scattered the studies made by a group of investigators working in general from the same point of view and with similar technique and laboratory equipment. Such a compilation in part defeats its own purpose unless complete. We regret, therefore, to be compelled to omit from the initial volume so many of the studies issued from the laboratory during the period covered.

C. E. FERREE,
Director of Laboratory.

A NOTE ON THE DETERMINATION OF THE RETINA'S SENSITIVITY TO COLORED LIGHT IN TERMS OF RADIOMETRIC UNITS

By C. E. FERREE and GERTRUDE RAND
Bryn Mawr College

About a year ago¹ the writers undertook to determine the retina's sensitivity, relative and absolute, to colored light in terms of units that can be compared. Since several years will be required to complete this work, they have thought it best to publish a preliminary note showing briefly the purpose and scope of the investigation. The following points will serve to indicate what is being attempted in this study.

(1) All measurements of sensitivity will be made in radiometric terms. This will give an expression of the sensitivity of the retina in units which are directly comparable with one another. At present we have no direct estimate of the comparative sensitivity of the retina to the different colors further than is expressed, for example, by the relative width of the collimator-slit that has to be used to arouse color sensation when a light-source of a given candle-power is used. This kind of comparison is obviously unfair because such different amounts of energy are represented from point to point in the spectrum that a given width of slit would admit many times the amount of energy at one part of the spectrum that it would at another. In short, no adequate estimation and expression of the retina's sensitivity to color, comparative or absolute, can be made by means of the methods now in common use.²

¹ The first public statement of our intention to use radiometric units in the investigation of the retina's sensitivity to color was made to the committee in charge of the Sarah Berliner Research Fellowship, February 1, 1911.

² Two criticisms have been received from private sources which it may be well to take account of here. In one the possibility of a point of view is implied, in the other a point of view is stated. The point of view, the possibility of which is implied in the first criticism, is that it is not proper to estimate the sensitivity of the retina in terms of physical units, because it is generally conceded by modern investigators of color vision that the retinal processes which transform the physical energy of the color stimulus into nervous energy is essentially chemical in its nature; and one can not assume that a certain amount of physical energy arouses an equal amount of chemical energy in the retina, or that equal amounts of physical energy arouse equal amounts of chemical energy. In answer to this, the writers would point out that these chemical substances are a part of the retina and their respective iner-

(2) Comparisons of results on many other points with such disparate stimuli seem equally inadequate: the relative time required for the different color sensations to attain their maximum of intensity, or retinal inertia; the relative rate of fatigue to the different colors; after-image and contrast sensitivity, etc.³ In fact there is not a quantitative problem

tias constitute one set of factors that determines the sensitivity of the retina to the different colored lights. It is not necessary to assume, therefore, that a given amount of physical energy arouses an equal amount of chemical energy, etc., in order to make our determinations of the comparative sensitivity of the retina to the different colors in terms of physical units. That would be necessary only if we were trying to separate out the nerve filaments, and to measure or compare their sensitivity to the different colors in terms of physical units. But even in chemical theories when speaking of the comparative sensitivity of the retina to the different colors, we do not mean the comparative sensitivity of the nerve filaments alone. We include the reaction of the chemical substances as well. Our contention, then, is that if the determination of the comparative sensitivity of the retina to the different colors is a proper problem, the determination should be made in terms of quantities that can be compared. This can be done either *a*, by using lights equalized in energy and determining by means of a sectored disc the relative amounts of these lights that are required to arouse sensation; or *b*, by using lights representing different amounts of energy and measuring directly in terms of radiometric units the amounts required to arouse sensation. We scarcely need point out that in speaking of the comparative sensitivity of the retina to the different colors we are not raising a new problem, but are merely recognizing a very old one.

The second criticism is in substance that a quantitative comparison of the effect of the different wave-lengths on the retina is improper because the different wave-lengths constitute stimuli too different in kind to permit of such comparison. This criticism we leave open, because we do not wish to discuss in this paper the propriety of the problem of comparing sensitivities.

³ It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amount of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse positive sensation. If the former view should be held it will be convenient to start with stimuli equalized in energy, and to determine the relative amounts of light required to arouse the after-image or contrast sensation by means of a sectored disc. If the second view should be held, the energy of the lights used may first be rendered proportional to the sensitivity of the eye to the colors in question; and the liminal values may then be determined by means of the sectored disc. In each case the relative sensitivity may be expressed by the inverse ratio of the open to the closed sectors.

Similarly two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy

dealing with the comparative functioning of the retina to the different colors in which there does not seem to be a need for the regulation and estimation of the stimulus in terms of a common unit of measurement. It is the purpose of the writers to extend the work as fast as possible into these related fields.

(3) We wish to make a careful study of the sensitivity of the peripheral retina, quantitative⁴ and qualitative, in a large

of the lights may be made proportional to the sensitivity of the eye to the different colors.

The need in both the above cases is equally great for a method of regulating and determining the amounts of light to be used in terms of a common unit of measurement.

⁴The following are two of the points we wish to take up: (1) A determination will be made of the ratio of sensitivity of peripheral to central retina from point to point for a single color in several meridians. This will show at what rate the retina falls off in sensitivity in a single meridian, and how uniform this decrease is in the different meridians. We have found in a preliminary study that this knowledge is greatly needed in explaining certain phenomena of the peripheral retina. Furthermore, when this determination is made for each of the colors with which we wish to work, the ratios of sensitivity for these colors at all the points can be calculated and a definite answer can be given to the question whether or not uniformity of ratio obtains throughout the retina. This question has been given considerable importance in the discussion of color theories. (2) The limits of sensitivity will be investigated. In general two problems are involved here. (a) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (b) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors. The second problem is more complicated and will later be made the subject of a separate paper. A word indicating its relation to our present plan of work may, however, not be out of place here. It may be logically assumed, for example, that the Hering theory demands that wherever the blue-sensing substance is found, the yellow-sensing substance must also be found. We have no means of knowing where these substances are except by the sensations aroused. Speaking in terms of the theory, then, we have a right to assume that wherever the blue sensation can be aroused the yellow sensation should be able to be aroused also, provided a sufficiently intensive stimulus be used. If, therefore, in passing towards the periphery of the retina, a point be found where blue can be aroused and yellow can not, the evidence will be strongly in favor of the conclusion that no yellow substance is present, unless it can be shown that elsewhere in the retina so much greater energy of yellow light than of blue is required to arouse sensation that the amount needed for this far peripheral point is greater than can be obtained. To establish this point the comparative sensitivity to these colors would have to be obtained at various points in the retina. This would involve the determination of a ratio based upon the amounts of blue and yellow light required to arouse sensation. Two methods of measurement may be used. (a) The amounts needed may be measured directly by means of a thermopile of the type we use, or other sensitive radiometer. In a deter-

number of meridians. In general too much uniformity has been assumed with regard to the sensitivity of the peripheral retina. Generalizations of great importance to color theory have frequently been based upon the results of work in which careful investigation was made in only one or two meridians. The conception of stable colors, and its application in support of the Hering *Urfarben* may be taken as a fair example of a sweeping conclusion which is based upon work too limited in its range. With a careful standardization of factors, an investigation in any considerable number of meridians shows that stable colors do not exist.⁵ Many other points of interest have come out in our more detailed study of the peripheral retina. For example, we find in the periphery of the normal retina small areas which are exact replicas of the Schumann case of color-blindness.

(4) We wish to conduct our investigation in full daylight instead of in the dark room. This is to eliminate the influence of the field surrounding the colored stimulus and of the pre-exposure. When the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness,⁶ the induction takes place in different amounts for the different colors. This white, in proportion to its amount, reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. To eliminate this twofold unequal action, the surrounding

mination of limens the number of readings required would render this method tedious. (b) The energy of the two lights may be made equal by means of a thermopile and the final amounts required to arouse sensation may be secured by means of a sectored disc. From the ratio of open to closed sectors the amount the light is cut down in each case may be calculated and the ratios of energy may be determined from these amounts.

⁵ The following points are offered in support of the above statement.

(1) A red and green cannot be obtained which in every meridian of the peripheral retina will pass into gray without an intermediate change into yellow or blue. (2) The amount of blue that has to be added to a mixture of red and green to produce gray varies from point to point in a given meridian even where the extramacular region alone is considered. Further, a series of determinations made for a given meridian will not hold for the remaining meridians. (3) A red, green, and yellow can not be obtained which will not change in color-tone in passing from the center to the periphery of the retina in a single meridian.

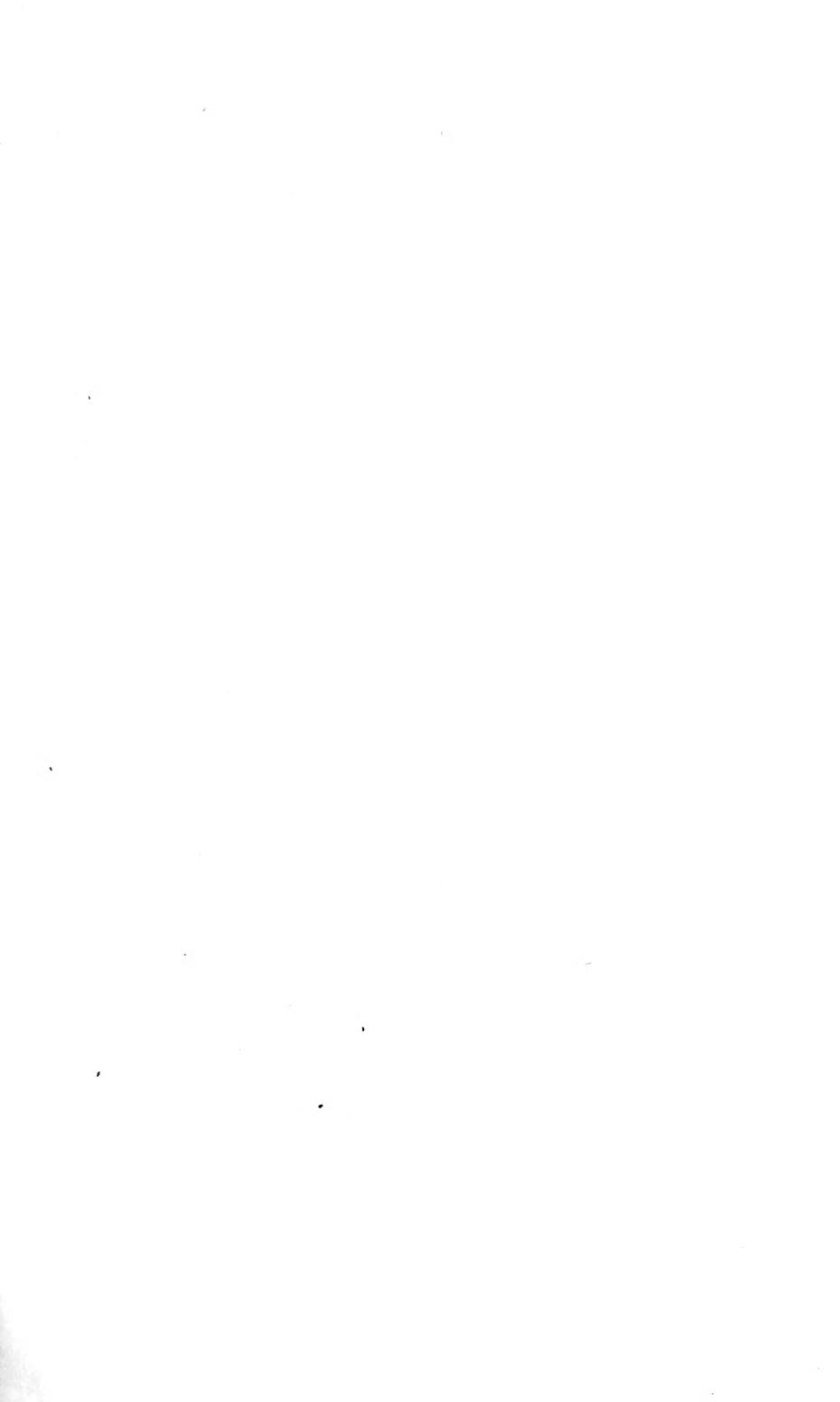
Blue alone of the four principal colors is stable in tone for all parts of the retina.

⁶ In a later paper one of the writers (Rand) will show that it is of no advantage to equate in brightness in determining the limits of color sensitivity, and that harm results in so many ways from the attempt to equate that it is doubtful whether it should be done even in determining the limens of color in the more sensitive parts of the retina.

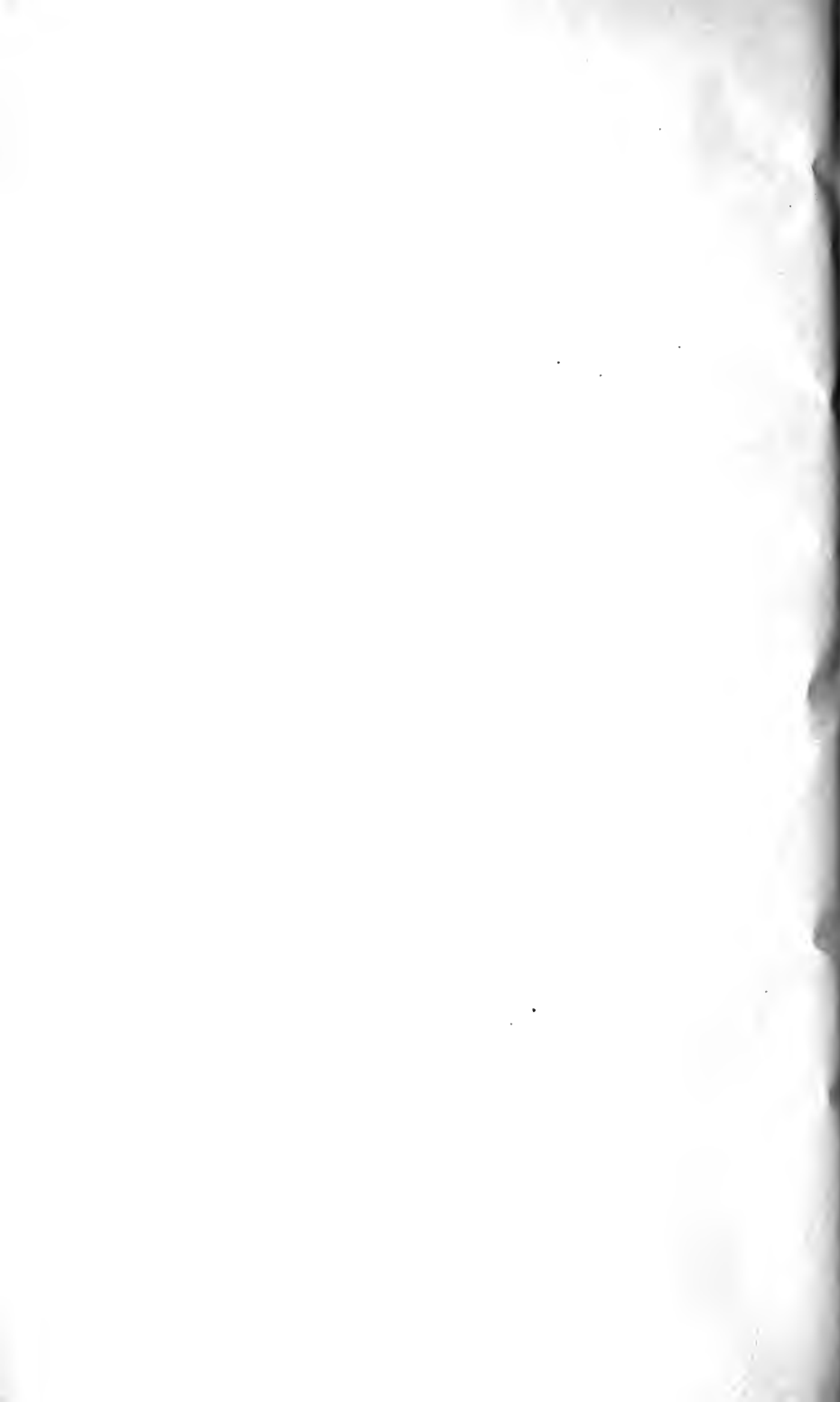
field should be made in each case of the brightness of the color to be used. This can be done by working in a light room of constant intensity of illumination and making the surrounding field of a gray paper of the brightness of the stimulus color. In order to accomplish this, and at the same time be able to work upon any meridian of the retina we choose, we have constructed a special piece of apparatus which we call a rotary campimeter. The influence of pre-exposure is even more important than of surrounding field. If the pre-exposure is to black, white is added as after-image to the stimulus color. The effect of a black pre-exposure upon the stimulus color is greater than the effect of a surrounding field of black, because more white is added as after-image of pre-exposure than is induced by contrast from the surrounding field. This effect also can be eliminated only by working in a light room of constant intensity of illumination and by choosing as pre-exposure a gray of the brightness of the color to be used.

We began a quantitative study of the factors that influence the sensitivity of the retina to color three years ago. With the control of factors we had at that time, we could not, for example, duplicate by several degrees at any two consecutive determinations the limits of the zone of sensitivity to any color. The result of our study has been that we are now able with a given light-source to duplicate, within a degree, the results obtained at a previous sitting. We can also duplicate, almost as closely, the threshold values or the amounts of light required to arouse color sensation in the more sensitive parts of the retina. Details of this work will not be given here. They will appear in a series of papers to be published in the course of the present year.

Having completed our work of standardizing the factors extraneous to the source of light, we are trying now to secure a better control of the source. Standardization, so far, can be considered successful only with regard to the quality of the light. No adequate work has been done upon the standardization of the quantity of light. We believe this can be accomplished only by means of energy determinations. We expect to do our radiometric work by means of a surface thermopile (Coblentz model), and a DuBois-Rubens *Panzer-galvanometer*, unless future results show that some other combination of radiometer and galvanometer is more satisfactory.







COLORED AFTER-IMAGE AND CONTRAST SENSATIONS FROM STIMULI IN WHICH NO COLOR IS SENSED

BY C. E. FERREE AND GERTRUDE RAND

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I. INTRODUCTION

In the March number of the PSYCHOLOGICAL REVIEW, 1907, Thompson and Gordon¹ describe a series of experiments in which colored after-images are obtained in the peripheral retina from stimuli in which no color was sensed. In the November number, 1905, and in the January number, 1908, of the same journal, Fernald² working under approximately the same condition reports similar results. In the *Proceedings of the American Philosophical Society*, 1908, however, Titchener and Pyle³ deny the phenomenon, affirming their complete inability to get colored after-images when no color is sensed in the stimulus.

¹ Thompson, H. B., and Gordon, K., 'A Study of After-images on the Peripheral Retina,' PSYCHOL. REV., 1907, XIV., pp. 122-167.

² Fernald, G. M., 'The Effect of the Brightness of Background on the Extent of the Color Fields and on the Color Tone in Peripheral Vision,' PSYCHOL. REV., 1905, XII., p. 405; 'The Effect of the Brightness of Background on the Appearance of Color Stimuli in Peripheral Vision,' PSYCHOL. REV., 1908, XV., pp. 33-35.

³ Titchener, E. B., and Pyle, W. H., 'On the After-images of Subliminally Colored Stimuli,' *Proc. of the Amer. Philos. Soc.*, 1908, XLVII., No. 189, pp. 366-384.

With regard to these discrepant reports, nothing more will be attempted at this place than to point out clearly the position held by each investigator. Titchener and Pyle contend that under no condition known to them can colored after-images be obtained from stimuli in which no color is sensed. Thompson and Gordon, and Fernald claim that under the conditions described by them, after-images may be obtained in which the color is clearly distinguished. The point at issue between them, then, is not whether the phenomenon can be gotten under this or that condition usually obtaining in the work on after-images, or under any given percentage of possible conditions, but whether it may be gotten by any experimental device whatsoever. Nor is it meant to extend the phenomenon to brightness sensation.¹ So far as the writers know, no one has ever claimed to be able to get an after-image from a brightness stimulus too weak to arouse sensation. The question, therefore, whether a subliminal sensory excitation can produce a supraliminal after-effect, considered in a general sense, is in no fashion under discussion. With the issue thus stated, the writers are impelled to take the affirmative side of the question by the experimental results they have obtained, and scarcely less strongly by theoretical considerations of the difference in the effect of different members of the brightness series upon all the colors when fused with them, and in the effect of a given brightness upon different colors. Working under the right conditions, the phenomenon is easily obtained. That its explanation is not essentially difficult will be shown in a later section of this paper.

The work on the peripheral retina has been repeated by the writers and the investigation extended to include other cases in which colored after-image and contrast sensations may be aroused by stimuli in which no color is sensed. It is the purpose of this report to describe these experiments and to explain the results obtained in terms of visual phenomena already known.

Before passing to a description of our own experiments it may be helpful to examine the work of previous investigators in

¹ For the sake of brevity, brightness is used here as a general term for the colorless sensation series, white, black and the grays.

order to determine from neutral ground if possible the cause of the disagreement in the results they have obtained.¹ In general two types of method have been used in arousing the color excitation. In one the color was kept below the limen of sensation by adaptation; in the other it was obscured by the action of an unfavorable brightness excitation. The former method was first used by Tschermak.² Tschermak's article is not a description of experimental work. It is an essay in which the author in part seeks to trace the analogies to visual adaptation found in the reactions of other tissue: muscle, nerve, secretory, etc., to external stimuli. The reference to the phenomenon we are discussing is very brief in this article and the description of the conditions under which it was obtained is quite inadequate to serve as a guide for future work. He says: "Haben wir doch gerade in der Anwendung des constanten Stromes auf Nerv und Muskel ein vorzügliches didaktisches Mittel, um die Grundbegriffe der allgemeinen Reiz- und Adaptationslehre zu veranschaulichen und einzuprägen. Am besten demonstrieren wir als Gegenstück zugleich die Wirkung eines mässig satten Farbglases auf das Auge: die Phase der Reizwirkung, individuell verschieden lang, und dadurch erinnernd an die verschiedenrasche Adaptation des Präparates vom Warmfrosch und Kaltfrosch an den constanten Strom—weiterhin das Stadium der vollendeten Adaptation, endlich den gegensinnigen Oeffnungseffect. Nicht minder lehrreich ist die Parallele des subjectiven und des objectiven Erscheinungsgebietes für das Phänomen des Einschleichens d. h. des Ausbleibens einer sinnfälligen Reizwirkung, wenn der Reiz so langsam anwächst, dass das Adaptationsvermögen folgen kann—gleichwohl hat auch nunmehr Wegfall des 'Reizes' eine gegensinnige Oeffnungswirkung. Analoges gilt vom Ausschleichen, also vom Ausbleiben eines sinnfälligen Oeffnungseffectes. Zum optischen Versuche schiebt man zweckmässig successive eine schwach tingierte Glasplatte vor die andere oder benützt einen Keil farbigen Glases."

¹ Because of the inadequacy of Tschermak's description of his method of working this can not be attempted for the work in the central retina.

² Tschermak, A., 'Das Anspannungsproblem in der Physiologie der Gegenwart,' *Archives des Sciences biologiques*, Sup. Band, 1904, XI, pp. 79-97.

In 1901 Titchener and Pyle carefully repeated and elaborated upon Tschermak's experiment on the central retina with entirely negative results. The writers can only commend the thoroughness with which they seem to have done this work. Their work on the peripheral retina is introduced with the following words. "We have already mentioned the experiments made by Titchener in 1906 with the view of testing the conclusions of Miss Fernald's first paper. The observations were rigorously confined to the black-white zone, and the outcome was definitely negative. In the meantime, however, the arousal of a colored after-image by a subliminally colored stimulus had been maintained for both the blue-yellow and the red-green zones. Unsystematic observations made in the Cornell Laboratory failed to confirm this result. It seemed worth while, however, to obtain further testimony; and Professor Baird, of the University of Illinois, very kindly consented to investigate the subject. The experiments were carried out by means of a simplified form of the Zimmermann perimeter, which permitted an accurate record of the degree of eccentricity at which the stimulus was exposed. Exploration was confined to the horizontal nasal meridian of each eye. The stimulus was a beam of light from an electric (16 c.p.) lamp, transmitted through appropriate combinations of gelatines and colored glasses; the colors employed were (non-equated) blue and yellow, red and green. Six of the most reliable laboratory students acted as observers, and Professor Baird had personal charge of the entire work. The after-images were projected upon white, gray and black grounds. The experiments proper were preceded by a careful determination of the outermost limits of color vision for the stimuli used, and all pains were taken to avoid chromatic adaptation" (pp. 376-377).

Professor Baird reports negative results in every instance. With regard to this work the writers can not help but observe that Baird has failed to conform to the conditions which Fernald had said are essential for getting the phenomenon. Without drawing upon their own experiments for a knowledge of essential conditions, they will point out three conditions which Baird has apparently failed to fulfill, the neglect of any

one of which is amply sufficient to account for his results being negative. (1) Fernald lays great stress upon the use of a campimeter screen by means of the induction from which the brightness conditions were obtained which obscured the color in her stimulus.¹ Baird used a simplified form of perimeter, how simplified Titchener and Pyle do not state. (2) Baird uses for the duration of the stimulation intervals of 30 to 40 seconds. Fernald is careful to state that the interval of stimulation should not exceed three seconds.² (3) In her description of conditions Fernald states that the color should be exposed behind the opening in a campimeter screen, and the card upon which the after-image is projected should be slipped in between the colored surface and the stimulus opening. Thereby the campimeter screen and thus the larger part of the field of vision remains unmoved and the least possible incentive is given for involuntary eye-movement. With Baird's apparatus, however, we would judge that the ground upon which the after-image was projected must have been moved in between the stimulus and the observer's eye, thus exerting a strong incentive to drag the fixation with it. A very slight eye-movement indeed is amply sufficient to blot out or to prevent from developing the instable peripheral after-image.

¹ While, as will be shown later in the article, the writers do not hold as Miss Fernald does that the inductive action of the campimeter screen is an essential or even a favorable condition, still they do insist that a campimeter screen or its equivalent is necessary in order to be able to give a projection field for the after-image without causing an amount of involuntary eye-movement that would prevent the momentary and instable peripheral after-image from developing.

² With regard to the importance of this point the writers are in entire agreement with Fernald. In fact one does not need to work long with peripheral after-images to be convinced that so long an interval as Baird used is absolutely prohibitive of colored after-images even when a less excentric portion of the retina is investigated than was the case here. A short interval of stimulation is necessary because of the rapid adaptation of the peripheral retina to color. It is well known that adaptation to color in any part of the retina takes place rapidly at first and then progressively more slowly until a stationary point is reached. Working in the central retina the writers have found a similar curve of effectiveness for after-images. After-images seem to occur most intensively when the stimulus is removed while adaptation is still going on. If one carries the stimulus beyond a stationary point in adaptation, the after-image will weaken roughly in proportion to the length of time during which the stimulus is regarded after the stationary point has been reached. This is true with both intensive and slightly supraliminal stimuli.

Failing to obtain the after-image in the central retina and to get confirmation by Baird that it may be obtained in the peripheral retina, Titchener and Pyle suggest explanations for the positive results gotten by Tschermak and Fernald. "The outcome of Tschermak's observations with the glass wedge must then in our opinion be explained by the prepossession of the observer and the roughness of the method employed. . . . It is less easy to account for the peripheral results." For a full statement of their explanation of the peripheral results the reader is referred to their article, pp. 378 ff. Brief mention only can be made of it here. We wish to comment on three points. (1) Their conception of the problem of getting color in the after-image when none is sensed in the stimulus is, we believe, different from that held and stated by Fernald. "The *experimentum crucis*," they say, "would be the production of a colored after-image in the achromatically adapted eye at a point lying well beyond the limits of blue-yellow vision." It is conceivable that two interpretations might be given to "well beyond the limits of blue-yellow vision." (a) The meaning might be well beyond the limits of blue-yellow vision whatever area and intensity of stimulus be used. And (b) it might be well beyond the limits at which these colors are seen when the stimuli used in the after-image experiments are employed. Wishing in every case to favor the point criticised, we choose the second interpretation. Thus to obtain a colored after-image well beyond the limits of blue-yellow vision would imply that a negative color excitation sufficiently strong to arouse sensation could occur in response to a stimulus which can under no condition arouse a positive color sensation. This is not at all the claim of Fernald nor of Thompson and Gordon as we understand their claim. They believe, in the cases cited by them, that the stimulus was prevented from arousing positive sensation by unfavorable brightness conditions. While it may not be clear from their work how these unfavorable brightness conditions prevent the positive sensation and permit the negative, there can hardly be any doubt that they would not claim that colored after-images can be aroused in the retina at a point "well beyond the limits of color vision." In fact in her

paper of 1905 Fernald specifically states that one should work just within the limits of color vision.¹

(2) It is pointed out by Titchener and Pyle that the limits obtained by Miss Fernald show a considerable range of variability. The "*experimentum crucis*" thus has been inadequately performed. She has in reality obtained the after-image within the limits of blue-yellow vision. As pointed out in (1), this, we believe, is not the point at issue. The question is not whether the after-image can be obtained beyond the limits of color vision, but whether it can be obtained anywhere in the retina when color is not sensed in the stimulus in a percentage of cases large enough to preclude the possibility of its being due to chance happening, to error of observation, or what not. Apparently neither Fernald nor Thompson and Gordon, and certainly not Tschermak, have entertained the idea that the colored after-image can be obtained at any point on the retina where experiment shows that color can not be obtained in the positive sensation for the given stimulus under any conditions whatever.

(3) Titchener and Pyle quote the following observations furnished by Miss Fernald by private correspondence.²

¹ In her paper of 1908 Fernald states that the after-images are perceived most frequently just inside or just beyond the regular limits for the color. As compared with her first statement, this may seem somewhat loose and might lead to misunderstanding. There can be little doubt, however, that beyond the regular limits means for her beyond the limits obtaining for some given set of brightness conditions taken as standard—not beyond the limits for all brightness conditions. Fernald, it will be remembered, worked with very little control of the factors extraneous to the source of light that influence the sensitivity of the retina to color. The boundaries of her color zones thus varied within quite wide limits. In this region through which the boundaries of the zones varied, she was able to obtain color in the after-image when none was sensed in the stimulus. Her 'regular' limits fell somewhere within this region. She was thus able to obtain the after-image sometimes just within, sometimes just beyond the regular limits. She apparently never obtained the after-image at a point beyond her widest limits of sensitivity to a given color. The present writers, working with a control of brightness conditions that enabled them to duplicate their limits from sitting to sitting within a degree of variation, never obtained the after-image beyond the limits determined under their most favorable brightness conditions.

² A request was sent to one of the present writers (Ferree) to determine whether these after-images could be gotten, at the same time the similar request was sent to Dr. Baird. The results quoted are samples of the observations made at that time.

Observer: C. E. Ferree. Full illumination on bright day (May 17, 1908). Nasal meridian, right. White ground. Projection field white, except in obs. 14-17, when it was black. Stimulus, 13 sq. mm. Distance from eye to stimulus, 25 cm.

Fixation Point	Stimulus	Color Seen	After-image
80°	<i>O</i>	Dark gray	Unsaturated light blue
85°	<i>B</i>	Just dark	Wash of unsaturated yellow
85°	<i>Y</i>	Nothing	Nothing
80°	<i>Y</i>	Tinge of dirty yellow	Very pale blue
80°	Medium gray	Dark	White
80°	<i>O</i>	Indefinite gray	Nothing
80°	Light gray	Dark	White
75°	<i>Y</i>	Reddish yellow	Good blue
75°	<i>B</i>	Good blue	Good yellow
75°	<i>B</i>	Good blue	Good yellow
65°	<i>O</i>	Yellowish red	Unsaturated blue
65°	<i>Y</i>	Reddish yellow	Blue
60°	<i>G</i>	Indefinite greenish gray	Uncertain
65°	<i>G</i>	Greenish yellow	Dark red, more saturated than stimulus
80°	Medium gray	Dark	Nothing
80°	Medium gray	Dark	Nothing
65°	<i>G</i>	No color	Flash of red
65°	<i>R</i>	No color	Blue

Commenting on these observations Titchener and Pyle say: "Positive results occur in the first two and last two observations of the series. The former may be explained in terms of chromatic adaptation. If as the illumination suggests the observer began the work in yellow adaptation, the first blue after-image would naturally follow." If the above explanation were adequate, the blue after-image should have been obtained also when gray was used as stimulus. As a check experiment gray was repeatedly used as stimulus by Fernald, and in no case was the characteristic blue after-image obtained.¹ Furthermore the same yellow light which in terms of the explanation gave the stimulation for the blue after-image fell with undiminished intensity on the projection field, hence there was no shutting off and, since the projection field was white, even no diminution

¹ In a footnote p. 382 we find: "These observations were taken after the limits had been roughly determined in previous experiments. If the determination of limits was made at the same sitting, and if the last test color employed was orange, there would be additional reason for an initial yellow-adaptation." In reply to this we would say that in case of our own experiments orange and yellow were purposely not the last colors used in determining the limits; that had they been, abundance of time was given for the complete recovery of the eye before the after-image experiments were performed; and that if chromatic adaptation had been present, its effect should have shown in the after-image when gray was used as stimulus.

in the amount of the yellow daylight reflected to the eye for the period during which the after-image was observed. Thus no chance was given for a blue after-image to develop as the result of stimulation by the yellow in the daylight. Continuing Titchener and Pyle say: "If the second observation was taken at too short an interval of time the resulting blue-adaptation should show itself as a yellow after-image." We interpret this statement with some hesitation. It seems to mean that the first observation gave a blue after-image, and that if the second observation followed too closely upon the first, this after-image excitation in turn aroused a negative excitation which formed the physiological basis of the yellow after-image observed. If this interpretation is correct two conclusions would logically follow. (1) A negative after-image can itself give a negative after-image,—a phenomenon which, so far as the writers know, has never yet been observed. And (2) although a colored stimulus too weak to arouse positive sensation can not arouse a colored after-image, still the excess of yellow in clear daylight, which, reflected from the yellow stimulus, is too weak to be sensed as color, can arouse an after-image which not only can be sensed as color but which in turn can arouse a second after-image in which color can be sensed. "The two final observations suggest a shift of conditions. Green is seen at 65° as greenish yellow and at 60° as indefinite greenish gray. It is possible that in the case in which 'no color' is reported the green simply escaped notice; peripheral colors at the limit of vision often appear as momentary flashes. Again red is reported at 65° as 'no color' although reddish yellow had been seen as far out as 75° . It is possible that the flash of red escaped notice; it is also possible that red-adaptation from the preceding after-image brought out the blue." With regard to the possibility of the red and green escaping notice, the following points may be noted. (1) The stimulus color in this region of the retina has not so much a momentary character as the after-image color and would, therefore, not be so likely to escape notice as the after-image color. (2) The observations quoted above were made by one of the writers (Ferree), who here positively asserts that to the best of his knowledge this

was not the case. (3) In our own experiments to be described later in this article, conditions were obtained under which the after-images of red and green were obtained in practically 100 per cent. of the observations made. It seems scarcely possible that the color should have escaped notice in the stimulus in all of these cases and have been observed in the after-image. In case it be held that "red-adaptation from the preceding after-image brought out the blue," we are again asked to accept the thesis that an after-image excitation may in turn give rise to an after-image excitation strong enough to be sensed as color.

II. CASES IN WHICH AFTER-IMAGES AND CONTRAST SENSATIONS ARE AROUSED BY RETINAL EXCITATIONS WHICH DO NOT DIRECTLY CONDITION SENSATION

1. *After-Images*

The problem presented is: Can the color in a stimulus be obscured directly for sensation, and still set up an excitation upon the retina which will give an after-image? Our answer is that it can be done both in the central and the peripheral retina, but possibly more readily in the latter than in the former. To accomplish it, an experimental condition must be devised which will work against the color in the stimulus and relatively favor it in the after-image. A working principle is found in the difference in effect of brightness changes upon the saturation of the colors.

This effect may be expressed as follows. (1) Brightness fused with color inhibits the color sensation. With the exception of the region just within the limit of sensitivity for two colors,¹ the following may be stated roughly as the law of this action for all colors for all parts of the retina. White inhibits

¹ Over a region 3° in width just within the limits of sensitivity as determined with the Hering pigment papers at full illumination, red and yellow have a higher limen in black than in white. In this zone red and yellow darken as compared with their brightness values in the central and paracentral retina. Added to the black of the disc, then, we have the black due to the darkening of the color. Thus the figures which are read from the disc do not express the actual amount of black added to the color. Whether or not we have an exception here to the law of the action of brightness upon color which obtains in the rest of the retina is thus open to question. At least, the exception as expressed by the measurements is exaggerated.

most, the grays in the order from light to dark next, and black the least. (2) A given brightness change does not affect all colors to the same extent. If local and towards either black or white, blue and green lose their saturation completely before red, orange, and yellow; when the change is general and toward black, produced by decrease of illumination, yellow, red, and dark orange are obscured before green and blue. All of these changes were utilized at different times in our experiments both on the central and peripheral retina. It is readily seen that the technique of getting a colored after-image from a stimulus in which no color is sensed becomes merely a matter of fusing the least favorable brightness quality with the stimulus color and the most favorable with the after-image color. When this technique was carried out in its best form, the colored after-image was obtained in practically every case.

i. In Central Vision

Two methods of working were used in these experiments, one in which the brightness control came through changes in the general illumination of the field of vision, and the other in which the changes were local. The former method will be described first.

After-images were obtained of red, yellow, and orange stimuli of the Hering series of colored papers. The work was done in a long narrow dark-room with a small window at one end near the center, darkened by a solid and carefully padded door. By opening and closing this door, the general illumination of the room could be varied at will. The observer was seated in front of the window and to the left, so that the light coming in from above and behind fell free from shadow upon a screen placed in front of him.

The intensity of the stimulus was decreased by decreasing the illumination. Two methods were used in doing this, differing in the amount of dark-adaptation the eye had experienced before the stimulus was given. In the first, a preliminary determination was made of the illumination at which the stimulus was sensed as colorless. The experiment was then conducted at that illumination. The stimulus was exposed

from 5 to 15 seconds, varying with the subject, and the after-image observed. In the second method, the experiment was started at full illumination. The door was opened and the stimulus covered with a card of the same gray as the background. The door was then closed rather quickly until the point was reached at which the color is unperceived, this point having previously been carefully determined. The stimulus was exposed before the eye had become adapted to the decreased illumination, and the after-image was observed. The advantage of the second method is that with it the eye loses its sensitivity to color at a more intensive illumination than when the first method is used. That is, the eye gains in sensitivity to color at any point in a series of decreasing illuminations if it is allowed to adapt to that illumination before the exposure is made. Thus, by taking advantage of the lessened sensitivity of the eye to color with decreased illumination before adaptation sets in, we were able to work at an illumination that gave a stronger objective stimulus, and was more favorable for the development of the after-image. Either method, however, gave us unmistakable color in the after-effect. In order that we might be sure that the observer worked with stimuli in which the color could not be sensed and that color really was distinguished in the after-image, he was in the first place kept in ignorance of the color that was to be used in a given test, and in the second place was given at intervals in the series a gray for stimulus which could not be distinguished from the color at that illumination. Thus having run blank tests, and having used every precaution known to us to eliminate the influence of expectation, etc., we feel a reasonable degree of confidence in the results obtained.

The after-images gotten in this way in central vision are not so saturated as those obtained in peripheral vision, but in proportion to their saturation last much longer than peripheral after-images. The after-image of red shows greatest saturation, dark orange next, and yellow least. As one would expect from its quicker rate of adaptation and from the fact that after-images decrease in intensity after the stationary-point in adaptation is reached, the time of stimulation most favorable for

producing the after-image was shorter for the red stimulus than for the other colors. The time for orange was next shortest, and for yellow the longest.

Local changes in the brightness of color may be produced by objective mixing, by contrast, and by after-image. Of these three methods the addition of brightness as after-image is by far the most successful. By objective mixing the amount of colored light coming to the eye is reduced in proportion to the amount of brightness added. The color thus loses saturation from two causes: the reduction of the amount of colored light coming to the eye, and the inhibitive action of the brightness excitation upon the color excitation. For our purpose, it is of advantage to obtain the loss in saturation without any reduction of the amount of colored light coming to the eye, *i. e.*, by means of the inhibitive action of the brightness excitation alone.¹ This can be done by the addition of the brightness either as contrast or as after-image. Of these two, the after-image method yields the better results, as much more brightness can be added as after-image than can be induced as contrast. This is especially true of the central retina. The amount of inhibitive action that can be obtained by this means may be shown as follows. The limen of Hering red in a gray of its own brightness is for one observer 27°. When the after-image obtained by a stimulation of 10 seconds to black is projected on this color, the limen is raised to 60°. This after-image decreases in intensity very little for the first 8 to 10 seconds, and disappears after from 12 to 15 seconds. 10 to 12 seconds stimulation to color is quite sufficient to arouse an intensive colored after-image. Hence by a preëxposure of 10 seconds to black and by the projection of the after-image upon a colored stimulus, it is possible to keep the color in a fairly intensive colored stimulus below the limen long enough to arouse the excitation necessary to give a colored after-image of considerable intensity.

The method of working is as follows. A small colored disc composed of sectors of the color to be used and a gray of the brightness of this color, is set up on a color-mixer. A second

¹ As will be shown in a later paper, this action inhibits the effect of the color excitation, although it does not reduce its power to arouse after-image and contrast.

disc of black of the same dimensions is set up beside it. As much color is put in the first disc as will be rendered just subliminal by the after-image obtained by a 10 second stimulation to the black disc. The colored after-image is then projected on a black field. The addition of white to the stimulus works against its color, and the black projection field favors the color of the after-image. Proceeding by this method, a colored after-image of good saturation and duration can be obtained in every case. The method can be made still more effective by adding the brightness to the stimulus color by both contrast and after-image. For example, the colored disc may be exposed through an opening in a black screen. The white induced by this screen would then add to the effect of the white after-image and in consequence still more color may be used as stimulus without arousing a color sensation.

ii. In Peripheral Vision

The color in the stimulus may be obscured in three ways. (a) It may be carried to the peripheral retina near the limit of sensitivity for the color used and a brightness be induced across it that works against its saturation. (b) The unfavorable brightness may be mixed with it as after-image aroused by preëxposure to a brightness stimulus. (c) The stimulus may be carried to some angle of indirect vision not too remote from the fovea and the general illumination be decreased until the color is lost. In (a) and (b) the brightness is mixed with the color by contrast and after-image rather than added to it on the color-wheel or by some other means of objective mixing, because, as stated before, objective mixing decreases the physical intensity of the stimulus. This would decrease the energy of the positive color excitation, which would in turn decrease the energy of the negative excitation, and thus defeat the purpose of the experiment. But the addition of the brightness as contrast or after-image does not affect the energy of the stimulus; and while it reduces the effect of the positive excitation upon sensation, it apparently does not decrease its energy as retinal excitation, for it does not lessen its power to arouse after-images. This strongly indicates that the action of bright-

ness upon color takes place at some physiological level posterior to the seat of the positive and negative color processes, as will be shown in the next paper of this series.¹ Consider method (*b*) for example. Here the brightness is added as after-image. Its effect is to blot out the weakly supraliminal color in the stimulus, but it does not prevent the complementary color from appearing in the after-image. This is readily explained in terms of the above hypothesis as to the level at which this action takes place. If, as we suppose, the inhibition takes place posterior to the level of the positive excitation, the negative excitation is not weakened thereby. And since the brightness after-image which was added cannot itself leave behind a brightness after-excitation, nothing is carried over to the negative color excitation to weaken its effect upon sensation. Hence by this method of working we should get as much color in the after-image as if no brightness quality had been added to the colored stimulus.

While method (*a*) can also be used to obscure the stimulus color, still it is not so effective as (*b*) for obtaining the colored after-image; because (1) by means of it the zone of sensitivity cannot be narrowed nearly so much as by (*b*), and (2) the inducing field throws by contrast the same brightness quality across the after-image as it does across the stimulus, and so, roughly speaking, it inhibits the after-image as much as it inhibits the stimulus.² In fact, in the way it has to be used in the peripheral retina method, (*a*) alone is of little use in getting our phenomenon. To make this method work successfully, some means would have to be devised for changing the quality of the inducing surface in the interval between the end of the stimulation and the beginning of the after-image. That is, the stimulation would have to be given on a field which induced a brightness quality unfavorable to the saturation of its color,

¹ See 'An Experimental Study of the Fusion of Colored and Colorless Light Sensations: The Physiological Level at which this Action Takes Place.' (In press.) See also abstract in *Journ. of Phil., Psych., and Scientific Methods*, 1911, VIII., p. 294.

² The second objection to this method does not apply to the use of the contrast method in the central retina (see p. 207), for in the central retina the colored after-image is sufficiently stable and durable so that an entirely new projection can be substituted for the screen which induces the contrast. In this case the effect of the induction of this screen can be eliminated from the after-image.

and the after-image observed on a field whose inductive action was favorable to the saturation of its color. This change of the inducing field, however, can not be made for two reasons. (1) The duration of the peripheral after-image is very short. It comes as a momentary flash of color immediately after the stimulus light is shut off, and disappears before a change in the inducing field can be made. And (2) the after-image would be completely extinguished by the eye movement set up by shifting so large a part of the field of vision.¹

The investigation of favorable conditions was conducted in part by means of the vertical campimeter and in part by means of the rotary campimeter.² The campimeter provides three possibilities for the variation of brightness conditions which was needed in our problem. By means of it, the brightness of the local preëxposure, the brightness of the inducing field, and the brightness of the field on which the after-image is projected may be changed at will. The brightness of the local preëxposure and of the field on which the after-image is projected may be varied by changing the cards held in the frame behind the stimulus opening in the campimeter screen. The brightness of the inducing field may be varied by changing the paper covering the campimeter screen. All of these variations were used in our investigation. Fernald recognized the influence of only two of these variations: the campimeter screen and the projection field.³ And of the two the importance of campimeter screen was very much overestimated, while the impor-

¹ See Ferree, C. E., 'The Fluctuation and Duration of the Negative After-image,' *Amer. Jour. of Psychol.*, 1908, XIX., pp. 68, 87-97.

² For a description of the vertical campimeter see Fernald, G. M., 'The Effect of the Brightness of Background on the Appearance of Color Stimuli in Peripheral Vision,' *Psychol. Rev.*, 1908, XV., pp. 27-29. For a description of the rotary campimeter see Ferree, C. E., 'A Description of a Rotary Campimeter,' *Amer. Jour. of Psychol.*, 1912, XXIII. (In press.)

³ The influence of preëxposure under the ordinary conditions of working was apparently not at all realized by her. Her preëxposure and projection field were in most cases made of the same brightness as the campimeter screen. No reason is assigned for doing this. Some indication of her reason may perhaps be had from Thompson and Gordon who also use a preëxposure and projection field of the same brightness as the campimeter screen. They say: "When the stimulation had lasted the desired time, the screen was again put over the color, thus making with the campimeter a uniform gray surface upon which the after-image could be observed" (*Psychol. Rev.*, 1907, XIV., p. 124).

tance of projection field was relatively underestimated. Moreover she seemed to entertain no clear notion of just how these factors produce their results. For example, the brightness induced by the campimeter screen was supposed to contribute in some fashion to the production of her phenomenon by working against the color in the stimulus and favoring it in the after-image; but just how it operates to do this was left in question. Apparently she had made no quantitative study of the fusion of brightness with color and of the relative influence of the different brightness qualities upon the saturation of color. From the side of explanation, then, she can scarcely be regarded as having a definite point from which to start.

Since the writers report the after-image in so much greater percentage of cases than Miss Fernald, and differ from her so much in their explanations of results, it may be well to discuss her work at this point in greater detail.¹ They have the following comments to make on her general technique and her explanation of how it produced the results she obtained.

1. No systematic attempt was made to determine the factors influencing her phenomenon. Of the full list of achromatic factors, for example: brightness of the surrounding field, brightness of the preëxposure,² brightness of the projection field, and the degree of general illumination, she recognizes only brightness of the surrounding field, brightness of the projection field, and the degree of general illumination. Especial stress is laid on the brightness of the surrounding field. As we have already shown, the influence of brightness of surrounding field is comparatively insignificant because it is exerted both upon the color of the stimulus and the color of the after-image. Thus if it is unfavorable to the one it will also be unfavorable to the other. It has a margin of influence, however, due to the fact that it does not act with equal strength upon the stimulus and the after-image. Its action is unequal because stimulus and after-image differ both in color and brightness. There would be on this account a small difference in the amount of induction by the screen in the two cases, due to the difference between the brightness relation of stimulus to background and that of after-image to background; and further a probable difference in the

¹ Fernald's work rather than Thompson and Gordon's is singled out at this point because Fernald has made a more extensive investigation of the brightness factors and their relation to the phenomenon in question than have Thompson and Gordon.

² Miss Fernald always used some kind of colorless preëxposure, but apparently she did not recognize its importance as a brightness factor. For her the preëxposure card served in the main merely as a neutral covering for the colored stimulus until a steady fixation could be obtained and the observer be otherwise made ready for the exposure to color. Towards the end of the work reported in 1909, however (p. 29), she apparently began to realize that if the fixation were held for a period varying from three to ten seconds, the preëxposure card would give a brightness after-image which would mix with the stimulus color and lighten or darken it, as the case might be. But under the ordinary conditions of working, she took no account of it as a brightness factor.

inhibitive action of this induced brightness upon the color, due to the fact that the stimulus and after-image are different colors. The factors of predominant importance are the brightness of the preëxposure and of the projection field. These are of greater importance (a) because more brightness influence can be exerted by means of them; and (b) because their action is more differential, *i. e.*, the brightness of the preëxposure acts upon the stimulus alone, and the brightness of the projection field acts upon the after-image alone. The brightness of the preëxposure can thus be made to work against the color in the stimulus and to have no effect upon the color in the after-image, and the brightness of the projection field can be made to favor the color in the after-image and to have no effect on the color of the stimulus.

2. No attempt was made to separate the achromatic factors and to study directly the relative importance of their effect upon the frequency with which the after-image may be obtained. However, in her study of the effect of achromatic conditions upon the limits of color sensitivity and upon color quality in stimulus and after-image, some attempt at separation was made, and in these experiments the observer was required to report cases in which color was sensed in the after-image when none was sensed in the stimulus. In order to study the effect of a given factor, the influence of all the factors but the one to be studied should be eliminated from the conditions of the experiment. If, for example, it were wanted to study the effect of the projection field, a gray of the brightness of the colored stimulus should have been chosen for the campimeter screen and preëxposure. In no case was this method of working employed. In her experiments to determine the effect of projection-field¹ the following conditions were used: The campimeter screens were platinum white, and black; the projection fields for each screen were in turn of black, white, and medium gray; and the preëxposure was in each case of the same brightness as the projection field. Since neither the preëxposure nor the screen was chosen of the brightness of the colored stimulus, all the factors were present in each case, instead of one. And in her experiments to determine the effect of surrounding field, screens of white, black, and gray of the brightness of the color were used with preëxposures and projection fields to match the screen in each case. In this case also it will be observed that when the brightness of the screen was varied the influence of neither of the other two factors was ruled out.

3. Her statement of the most favorable brightness conditions for getting the after-image is in complete contradiction to all we have been able to find out directly concerning the phenomenon, or to infer from our investigations of the action of brightness upon color either in the positive sensation or in the after-image. For example, she states that white campimeter screen and a white projection field give the most favorable conditions for obtaining after-images of blue and yellow when no color was sensed in the stimulus. Stating her most favorable conditions for the after-images of red and green, she says: "In several instances in our later work a red after-image has followed an unperceived green when the stimulus was given on a white background and the dark screen [projection field] pushed over the color, and a green after-image was obtained for red and orange when the projection-screen was middle gray or black."² The writers were able to obtain after-images of the above colors under the conditions cited by Miss Fernald as most favorable, but instead of finding them to be the most favorable they found them to be almost the most unfavorable. As stated above, their most favorable conditions were black preëxposure, black campimeter screen, black projection field; and their most unfavorable conditions were white preëxposure, white

¹ Fernald, G. M., *PSYCHOL. REV. MONOG.*, 1909, X., pp. 37-45.

² *Op. cit.*, p. 82.

campimeter screen, and white projection field. The variation of the factors between these extremes gave the phenomenon with a frequency ranging between maximal and minimal. Working with the conditions she found to be most favorable, Miss Fernald was able to obtain the after-image in only approximately 31 per cent. of the total number of cases.¹ With the conditions we have found to be most favorable the after-image may be obtained in practically every case.

4. Miss Fernald's explanation of her results is also in contradiction to the facts as we find them. (a) She says that the most favorable conditions are gotten when the "projection-screens were determined so as most to emphasize the after-image color and the background least to favor the stimulus color."² The campimeter screen, then, that narrows the zone of sensitivity for a given color furnishes the most favorable conditions to be obtained for that color. The white screen is most favorable because "in so far as our results justify any conclusions concerning the color limit they seem to show that all the colors except the reds are perceived at a greater degree of eccentricity with the dark than with the light backgrounds. Red is seen as red to about the *same* degree of eccentricity with the dark and light backgrounds, but it is seen as yellow or orange with the dark background at the same points at which it is seen as colorless with the light background."³ Her exception in case of red seems due to the fact that the limit for red is for her where first a trace of yellow comes in. If the limit for red had been taken at the point where the last trace of red is seen, as is usually done, red would have proved no exception to the other colors, and we could derive from her results the law that all the colors have a narrower limit with the white screen than with the dark or black screens. We do not find this to be true. For us blue and green have a wider limit with the black screen than with the white, and red and yellow a narrower limit. These results were obtained with the effect of preëxposure eliminated and with the illumination of the optics room carefully standardized by a method to be described in a later paper. Neither of these precautions was observed in Fernald's work. Their importance may be shown by the following results. As compared with the gray of the brightness of the color, a preëxposure of three seconds to black was found by one of the writers (Rand) to narrow the limits of sensitivity for red, green, and yellow 6°, and for blue 11°; a preëxposure to white to narrow the limits for red 5°, for green 2°, for yellow 4°, for blue 7°. At an eccentricity of 35° on the temporal meridian, a preëxposure of three seconds to black raised the limen for red 58°, for green 80°, for yellow 32°, and for blue 13°; a preëxposure to white raised the limen for red 45°, for green 55°, for yellow 12°, and for blue 7°. When the white campimeter screen was used, the changes in illumination from 11 A.M. until 4 P.M. on a bright day in September were found to vary the limits for the different colors from 4° to 6°. The change in the illumination of our optics room, lighted by skylight and provided with diffusion sashes to lessen the effect of external changes, from a bright morning to a cloudy afternoon was sufficient to vary the limits with a white screen from 6° to 14° for the different colors; and with a black screen from 2° to 7°. The greater variability is found for the white screen because the amount of contrast it induces is found to vary more with the change of illumination. (b) Miss Fernald seems to believe that the brightness process may have either a stimulating or an inhibiting effect on the color process. She says: "There seem to be two possible ways of explaining the action of brightness: Either the brightness of the stimulus has a direct inhibitory or stimulating

¹ Fernald, G., *PSYCHOL. REV.*, 1908, XV., p. 33.

² Fernald, G., *PSYCHOL. REV. MONOG. SUP.*, 1909, X., p. 82.

³ *Op. cit.*, p. 23.

effect on the color processes, or the brightness primarily affects the brightness substance, and the activity in brightness substance has some differential effect on the color activity. . . . The fact that our most striking effects were obtained when the brightness is superimposed on the color, *i. e.*, when the brightness is largely determined by contrast with a brightness background, or when the after-image is projected on a light or dark ground, seems at least to justify the statement that the superimposed brightness acts in such a way as to inhibit, increase, or modify the color activity.”¹ Her claim that all the colors have their widest limits with the black screen and their narrowest with the white seems to indicate that she considers that white increases the color activity and that black decreases it. She says: “This brightness factor is effective to a very limited extent in central vision, to a much greater extent in peripheral vision. As we go out into the peripheral retina, the action of the white process is needed more and more, *i. e.*, the colors must be made lighter to be most strongly sensed.”² Our results show that the brightness process, white, black, or gray, must be considered as always having an inhibitive action on the color processes. When the brightness process is added to the color process either as after-image or contrast, the amount of colored light coming to the eye remains unchanged and yet the saturation of the color is considerably decreased. Instead of being increased by the action of white and decreased by the action of black the saturation is decreased by the action of both, but much the most by the action of white for all colors for all parts of the retina with the exception of for red and yellow within a very narrow zone just within the limits of sensitivity. In this zone red and yellow have a higher limen in black than in white. It is not certain, however, that even in this zone black exerts the greater inhibitive action, for it is difficult to add the same amounts of black and white to red and yellow because these colors darken in the peripheral retina and it is hard to get a measure of how much black is added by this process alone. The relative amounts of inhibitive action by white, black, and gray of the brightness of the color can also be shown by the method of objective mixing. When equal amounts of white, black, and the gray are added in turn to a disc of color on the color mixer, the colored light coming to the eye is reduced an equal amount in each case, yet the apparent saturation of the color is very different on the three discs. It is much the greatest on the disc to which black has been added, next greatest on the disc to which gray has been added, and the least on the disc to which white has been added. Or to get a more exact measurement of the actions in each case, the color limen may be determined. An amount of color which is just noticeable when added to the black disc will give no color at all when added to the white or gray disc. A considerably larger amount must be added to the gray disc to give color, and a still larger amount must be added to the white disc than was added to the gray disc.

Such a confusion as Miss Fernald and many others before her have fallen into with regard to the relation of brightness to intensity or strength of color is apt to come from the failure to separate the action of the brightness or achromatic excitation from the action of physical intensity or energy of the light waves coming to the eye. When a colored light of low energy strikes the eye it is both unsaturated as to color and for the most of the colors of low brightness. As its energy is increased it becomes more strongly sensed as color and in most cases lighter. That the two changes go hand in hand when the physical energy of the colored light is changed, however, does not justify the inference that they will go hand in hand when there is no change in the energy

¹ *Op. cit.*, p. 79.

² *Op. cit.*, p. 73.

of the colored light—in other words does not justify the inference that an increase in the white excitation will heighten the color excitation. The central principle of Miss Fernald's method of working is to change the achromatic excitation without affecting the amount of colored light coming to the eye. In all such cases, with the possible exception of red and yellow for the small zone mentioned above, the saturation of the color decreases rapidly as the quality of the achromatic component is made lighter. In addition it is scarcely necessary to point out that just because a color reaches its maximal saturation at a given brightness as the energy of the colored light is increased, it does not follow that the achromatic excitation corresponding to this brightness is the most favorable in its action upon the color process. When the amount of colored light is rendered constant and the achromatic factor is varied, it is found that black is the most favorable quality of the achromatic series and the specific grays are favorable in proportion as they are near to black in quality. The gray of the brightness of yellow, for example, kills out the color in yellow when mixed with it almost as rapidly as does white and much more rapidly than does black and the darker grays. Thompson and Gordon, while in general agreeing with Fernald with regard to the effect of brightness relations, in one place seem both in addition and in contradiction to have fallen into this latter error. They say: "The effect of the background then seems to be this; that in a colored after-image, that color element is emphasized which in brightness approaches the brightness of the background [by background is meant here the field on which the after-image is projected], that is, on the lighter grounds the brighter element comes out and on the darker grounds the darker color element."¹

By way of clearing the ground for explanation, the writers have made a detailed study of the influence of the various brightness qualities upon color in the central retina, and for a large number of meridians in the peripheral retina. Since a statement of the results obtained will be given in full in a later paper, nothing more than a general statement will be attempted here. In the central retina, white reduces the saturation of colors the most, the grays in the order from light to dark next, and black the least. In the peripheral retina, this law holds for blue and green out to the limit of sensitivity for all of the observers worked with; and also for red and yellow for all of the peripheral retina except a very narrow zone just within the limit of sensitivity. In this zone, black apparently inhibits red and yellow most strongly—at least, red and yellow have a higher limen here when mixed with black than when mixed with white or the grays. An ultimate statement of most favorable conditions for all parts of the retina, then, would have to take into consideration all of the facts. It would involve a more detailed consideration of the topography of the retina than can be gone into in this paper. In formulating our

¹ Thompson and Gordon, *op. cit.*, p. 128.

experimental technique, however, we have avoided, we believe, the difficulty raised by the exception to the law found just within the limit of sensitivity by employing inhibitive conditions sufficiently strong to allow us to work nearer the center of the retina, where the exception has never been found. Thus we have been able to use as our working principle the law that white inhibits the most, grays in the order from light to dark next, and black the least. But to determine in accord with the law even thus simply stated, the brightness quality of preëxposure, campimeter screen, and projection field that will give the conditions most unfavorable for the stimulus color and most favorable for the after-image color, is not easy. For example, in order to inhibit the stimulus color most strongly, the preëxposure must be black, so as to give a white after-image to fuse with the color. This effect could be strongly intensified by having the black preëxposure made through an opening in a white campimeter screen, and the color exposure, which comes immediately after and simultaneously with the after-image of the black preëxposure, made through a black screen. This would secure the greatest possible intensification of the white after-image, and, therefore, the greatest possible amount of inhibition of the stimulus color. In order to favor maximally the saturation of the after-image color, the after-image should be projected on a field of very dark gray or black.¹ As to campimeter screens to be used during the projection of the after-image, we have a choice again of brightness qualities ranging from white to black. White and the grays in proportion to their whiteness would intensify by contrast the blackness of the projection field, while black would exert little if any influence. The black screen, then, is probably the safest to use while the after-image is being observed for two reasons. (1) If one is working with a general illumination at all intensive, white and the grays in proportion to their whiteness induce enormously in the peripheral retina. This amount of induction of black carries the brightness quality beyond that

¹ It may be well to state that in our study of the effect of brightness upon color, the black used was the matt black of the Hering papers. When we state that black favors the saturation of colors, this black is referred to.

specified in our law as most favorable, namely, the blackness of the pigment of the Hering paper. (2) There is always danger that we may not be working far enough within the limit of sensitivity to escape the exception to our law of most favorable action. If, then, our formulation of conditions be correct, we should have a white campimeter screen during preëxposure to black, and a black screen during both the exposure of the stimulus color and the projection of the after-image. This would involve two changes of the card behind the stimulus opening in the screen, and one change of the screen. The change of cards causes no disturbance in our phenomenon, but a change of the campimeter screen in the interval between the preëxposure and the exposure to color would be fatal to the success of our experiments. This is because the white after-image would not last through the change, for reasons that have already been discussed; and the effect of the preëxposure on the stimulus color would therefore be lost. We are thus limited to one screen for a single experiment, and our problem becomes to determine which of the brightness qualities acting continuously through all three stages of the experiment will be the most favorable for our phenomenon. After rough preliminary tests, three screens were selected as representative of the action of all, namely, white, black, and a gray of the brightness of the color to be used. Of these three, the black screen was found to be much the most favorable. A consideration of the action of the three brightness qualities upon preëxposure, stimulus color, and after-image shows sufficient reason for this. The effect of each is as follows: (1) The white screen intensifies the blackness of the preëxposure, darkens the stimulus card, and, in the peripheral retina, especially if the general illumination is intensive, piles up the blackness on the projection field to a degree that is unfavorable to the saturation of the after-image color. (2) The gray screen of the same brightness as the color adds blackness both to the preëxposure and to the projection field, but not so much as is added by the white screen. It has no effect on the stimulus card. (3) The black screen has no effect on the preëxposure; it induces white on the stimulus card and thus adds to the

effect of the preëxposure on the stimulus color; and it exerts little or no effect on the projection field. A comparison of these effects shows that the black screen in all probability inhibits the stimulus color more than any of the others, and is less unfavorable in its action upon the after-image color. For this reason, it gives the most favorable brightness conditions for obtaining our phenomenon. Considering all the factors, then, we find that apparently the most favorable combination that can be made for our purpose is black preëxposure, black campimeter screen, and black projection field. The results of our experiments show this to be true. Under these conditions, color was obtained in the after-image in practically every case. The next most favorable condition was given by the white or gray screen with black preëxposure and black projection field. The poorest results were obtained with a white preëxposure and white projection field. With this combination, color could not be gotten in the after-image with any consistency of result, whatever brightness quality was used in the campimeter screen.

Having thus worked our way through an explanation of our phenomenon and a determination of the conditions under which it can best be obtained, we will devote the remainder of the report of the work done by methods (a) and (b) to a brief review of the results obtained in support of the various points that have been made. Our general thesis was that the phenomenon under consideration is but a special case of the difference in the inhibitive action exerted upon color by the different brightness qualities. Color may be obtained in the after-image when none is sensed in the stimulus, if an unfavorable brightness quality is fused with the stimulus color and a favorable one with the after-image color. In detail, our first point was that for all parts of the retina and for all colors, with the exception of two over a narrow zone just within the limits of sensitivity, white reduces the saturation of color the most, the grays in the order from light to dark next, and black the least. This law was generalized from the results of fusion and limen experiments in a large number of meridians of the retina. Our second point was that the combination of the preëxposure and campimeter screen

most unfavorable to the saturation of the stimulus color was the most favorable condition for obtaining our phenomenon. The effect of preëxposure and campimeter screen upon the saturation of the stimulus color was measured in two ways: (1) by the effect on the limen color; and (2) by the effect on the limits of sensitivity.¹ Data were thus obtained which we could directly correlate with the frequency with which color was obtained in the after-image, and so determine whether our position was correctly taken. The results of this correlation show that, estimated in both these ways, the combination that proved the least favorable to the saturation of the stimulus gave color in the after-image in the largest percentage of cases; and, conversely, that the combination most favorable in its action on the stimulus gave color in the after-image in the smallest percentage of cases. A third point was that a black preëxposure and black screen gave the brightness conditions that were most unfavorable to the saturation of the stimulus color. An estimation of the effect of the different combinations of screen and preëxposure by either of the methods mentioned above brings out this point strongly. The least effect was found when preëxposure and screen were both of the brightness of the stimulus color. A fourth point was that preëxposure provides a stronger means of reducing the saturation of the stimulus color than does the screen. To make the test of this point absolute, the influence of one should be completely eliminated while the influence of the other is being determined. This can not be done. The eye must always have some preëxposure, and there will

¹ See Rand, G., 'The Factors Which Influence the Campimetrical Observation: A Quantitative Examination and Methods of Standardizing.' (In press.)

Of these two tests, the limen test has a much broader application, and measures much more directly what needs to be measured. It has a broader application because it can be made anywhere in the zone of sensitivity. It measures more directly what needs to be measured, because the results obtained show just how much color has to be present under a given condition to be sensed as color, while the results in the method of limits only express in terms of degrees how much the limit of sensitivity has been changed. This is a poor measure of how much the color in the stimulus has been inhibited under a given condition: because, in the first place, it is not a direct measure of this action; and, in the second place, the results obtained cannot be even roughly rendered into terms of direct measurement, owing to the fact that the sensitivity of the retina near the limits does not fall off either gradually or regularly.

always be a surrounding field. The effect of preëxposure, however, can be minimized by choosing it of the gray of the brightness of the color to be used as stimulus, and by making the stimulation to it extremely short. Working in this fashion, we have only a slight local brightness adaptation to modify the color excitation immediately following, the effect of which can be taken as practically negligible. The influence of the screen also can be minimized in a similar way, by having it always of the brightness of the color to be used as stimulus. Isolating the action of preëxposure and screen by this method, we estimated the effect of each in turn upon the saturation of the stimulus color, both by the effect on the limen of color and on the limits of sensitivity. Our results in both cases show that preëxposure can be made much the stronger factor. For example, the limits of sensitivity were never made to vary more than 4° by the most extreme changes that could be made in screens, while it could be varied as much as 14° by changes in the preëxposure. The difference stands out still more strongly in the effect on the limen, as would naturally be expected, since changes in the limen more directly express the differences in the inhibitive action than changes in the limits of sensitivity, as was shown in the footnote, p. 219. A fifth point was that black is the most favorable brightness quality for the projection field. This was shown very clearly by using projection fields of white, gray of the brightness of the stimulus color, and black, with each of the combinations of preëxposure and screen, and comparing the results obtained. In addition, these results, when compared with those obtained by varying the preëxposure and the campimeter screen, show that the brightness of the projection field is a very important factor—much more important than the brightness of the campimeter screen, and just as important, possibly more so than the brightness of the preëxposure.

Results in support of these points in general are given in Table I. In this table is shown the percentage of cases, based on twenty trials, in which color was obtained in the after-image when none was sensed in the stimulus. The object of the experiments was to determine the relative importance of the

three factors, preëxposure, campimeter screen, and projection field. The method of experimenting in the following cases was to keep two of the factors constant and find the effect of varying the third. However, in order to show most effectively the most favorable conditions in decreasing order, the results have been grouped as follows. If the individual, horizontal columns are compared, the effect of campimeter screen is shown. If groups of three are compared, the effect of preëxposure is seen. If compared in groups of nine, the effect of projection is seen.

From the table it will be seen that projection field and preëxposure are the most important factors. Of the pre-exposures, black is seen to be the most important. Its effect is greater on green and blue than on red and yellow. This is because the inhibitive action of the white after-image following the preëxposure is greater for blue and green than for red and yellow. The full effect of preëxposure was not obtained in our experiments because with a given black preëxposure we did not work as near the center of the retina as we might have done.

In method (c) also (see p. 208), the vertical campimeter was used to give the stimulus. Black was chosen both for the campimeter screen and for the projection screen in each case. Otherwise the procedure was the same as for after-images in direct vision. The results obtained were also similar, with the exception that not so much decrease of illumination was needed to obscure the stimulus color, and more saturated after-images were obtained. The stimulus time in indirect vision must always be shorter than in direct vision. (From 2 to 3 seconds was used.) This is due to the rapid exhaustion to color in indirect vision. After-images fall off in saturation if exhaustion to the stimulus color is carried beyond the stationary-point.

2. Contrast

It was found that contrast could be induced for certain colors when the general illumination was sufficiently reduced to obscure the color in the inducing stimulus. Very strong

TABLE I

SHOWING THE PERCENTAGE OF CASES IN WHICH THE COLORED AFTER-IMAGE WAS OBTAINED WHEN NO COLOR WAS SENSED IN THE STIMULUS, UNDER ALL VARIATIONS OF SCREEN, PREEXPOSURE, AND PROJECTION FIELD

Campimeter Screen	Preexposure	Projection	Red	Yellow	Green	Blue
Black	Black	Black	100	100	100	100
Gray	Black	Black	100	100	80	70
White	Black	Black	50	40	50	40
Black	Gray	Black	40	30	30	20
Gray	Gray	Black	50	30	0	0
White	Gray	Black	50	40	0	0
Black	White	Black	50	30	40	0
Gray	White	Black	45	20	0	0
White	White	Black	45	30	0	0
Black	Black	Gray	40	70	50	40
Gray	Black	Gray	20	40	20	20
White	Black	Gray	20	30	0	0
Black	Gray	Gray	0	0	0	0
Gray	Gray	Gray	0	0	0	0
White	Gray	Gray	0	0	0	0
Black	White	Gray	0	10	0	0
Gray	White	Gray	0	0	0	0
White	White	Gray	0	10	0	0
Black	Black	White	0	0	10	0
Gray	Black	White	0	0	0	0
White	Black	White	0	20	0	0
Black	Gray	White	0	0	0	0
Gray	Gray	White	0	0	0	0
White	Gray	White	0	0	0	0
Black	White	White	0	0	0	0
Gray	White	White	0	0	0	0
White	White	White	0	0	0	0

contrast was aroused under these conditions by standard red, dark orange, and yellow of the Hering series of colored papers.

Contrast discs were cut as follows. The inducing surface was made of two colored discs; one 25 cm., the other 10.5 cm. in diameter. The contrast surface was made by placing between these discs on the color-mixer a black and white disc, 11.5 cm. in diameter. When these were rotated, the black and white mixed to give a gray ring 1 cm. in width, separating the two colored surfaces. The proportions of black and white were taken so that the gray ring matched in brightness the

color used, the brightness of the color having been determined by means of Schenck's flicker photometer.

The observations were made in the dark-room described above. The color of the inducing surface was obscured by a decrease of the illumination. As in the after-image experiments, this was done by two methods, one in which the observation was made after the eye had adapted to the illumination chosen; the other before adaptation had set in. The latter method gave a much stronger effect, for although decrease of illumination within wide limits increases contrast effect in general, this increase is very much greater while the illumination is decreasing. That is, if two determinations of contrast are made for the same inducing and contrast surfaces, one in which the judgment is passed while the illumination is decreasing, the other after the eye has become adapted to the illumination at which the former judgment was made, it will be found that the former determination greatly exceeds the latter. Thus it appears that color induction is greatly enhanced while the retinal change corresponding to dark-adaptation is going on. This phenomenon will be treated more fully in a later paper on contrast. Our present purpose is satisfied with the consideration of the phenomenon at one point in the series of decreasing illumination; namely, the point at which the color in the inducing surface is obscured. This point varies greatly for the different colors used. It is the highest for red, next highest for yellow and dark orange, lowest for green, and next lowest for blue.

The amount of contrast induced in each case was determined by two methods. In each method a measuring-disc was used, compounded from discs of the proper colors and of black and white. In the first method, the comparison-judgment between the contrast ring and the measuring-disc was made at the illumination at which the inducing color was obscured. This method may not be clear to the reader. It may seem, for example, that a degree of illumination that wholly obscures the inducing color would also wholly obscure the color of the measuring-disc. This is not true because of the different effect of the decrease of illumination upon the saturation of the dif-

ferent colors, *i. e.*, blue, green, and blue-green, the colors used for the measuring-discs, retain considerable color at the illumination at which red, yellow, and dark orange, the inducing colors used, lose their saturation. The difficulty with the method is, that the measurements on the comparison-disc at a low illumination are not of standard value because of decrease of saturation, and thus convey little meaning to the mind of the reader. In order to get measurements in standard terms, a second method was resorted to, the results of which are more intelligible although the method of judgment is less accurate. In this method the comparison was made in terms of the saturation of colors on the measuring-disc at full illumination. Since one of the terms of comparison is a memory-image, a time error was involved in this method. This was to some extent compensated for, however, by working both ways, *i. e.*, a part of the judgments were made by first getting a memory-image of the contrast sensation at decreased illumination and comparing that with the measuring-disc at full illumination, and a part were made by the inverse procedure.

The tables recorded in the report are compiled from the results of Misses Chamberlain (*C*) and Rand (*R*), fellows in psychology, of Bryn Mawr College, and Bunker (*B*), graduate student.

3. *The Purkinje-Brücke Phenomenon*

The Purkinje-Brücke phenomenon was found by us to demonstrate in a very striking fashion that it is not necessary for the inducing excitation to condition sensation directly in order that color induction may take place.

This phenomenon was first described by Purkinje in 1825.¹ He says: "Man liege ein weisses Quadrätchen von der Breite zweier Linien auf einen schwarzen Grund, starre es 20-30 Secunden an, und blicke sodann ins Schwarze hinein, so wird man ein noch dunkleres Viereck sehen, dessen Randes mit einem graulichen, sich allmählich verlierenden Scheine umgeben sind. Lagt man auf den schwarzen Grund statt des weissen Quadrätchens ein rothes, so zeigt sein grünes Spectrum einen

¹ Purkinje, J., 'Beobachtungen und Versuche zur Physiologie die Sinne,' 1825, II., p. 107.

TABLE II

C. SHOWING THE AMOUNT OF CONTRAST INDUCED WHEN THE COLOR IN THE INDUCING SURFACE IS UNSENSED

Stimulus	Contrast Ring	Direct Judgment	Memory-image Judgment
Red.....	White 41° Black 319°	Green 130° Black 230°	Green 171° Black 119° White 70°
Yellow.....	White 236° Black 124°	Blue 151° Black 130° White 79°	Blue 76° Black 223° White 61°
Dark orange.....	White 82° Black 278°	Green 210° Blue 56° Black 94°	Green 168° Blue 14° Black 172° White 6°

TABLE III

OBSERVER B

Stimulus	Contrast Ring	Direct Judgment	Memory-image Judgment
Red.....	White 41° Black 319°	Green 228° Black 132°	Green 214° Black 94° White 52°
Yellow.....	White 236° Black 124°	Blue 121° Black 142° White 97°	Blue 163° Black 59° White 138°
Dark orange.....	White 82° Black 278°	Green 136° Blue 118° Black 106°	Green 152° Blue 106° Black 102°

TABLE IV

OBSERVER R

Stimulus	Contrast Ring	Direct Judgment	Memory-image Judgment
Red.....	White 41° Black 319°	Green 225° Black 135°	Green 166° Black 126° White 68°
Yellow.....	White 236° Black 124°	Blue 137° Black 189° White 34°	Blue 82° Black 159° White 119°
Dark orange.....	White 82° Black 278°	Green 195° Blue 64° Black 52° White 49°	Green 127° Blue 44° Black 159° White 30°

rothlichen Schein; auf gleiche Weise das blaue Spectrum einen orangen Schein, u.s.w. Man sieht heraus dass die objective Farbe nicht bloss in die Tiefe der Retina, sondern auch in die Breite einwirkt jedoch nicht gleich mässig nach ihrer ganzen Ausbreitung, sondern zunächst an der Gränze der heterogenen Beleuchtungen am intensivesten."

The phenomenon with some modifications was next described by Brücke in 1851,¹ and by Aubert in 1862.² The color or added brightness in the after-image was called by Brücke an after-effect of induction;³ by Aubert an after-image of contrast. Attention was again called to the phenomenon by Hering in

¹ Brücke (*Pogg. Ann.*, 1851, LXXXIV., pp. 418-448) says (p. 47): "Einen dritten Beweis endlich kaum man aus der Beobachtung der negativen Nachbilder entnehmen, welche nach diesem Versuchen zur Erscheinung kommen welche zeigen, dass die inducirten Farben als solche im Stande sind, complementären gefärbte Nachbilder hervorzurufen." His demonstration consists in getting the after-effect of looking towards the light through squares of red, green and violet glass with small discs of black paper placed at their centers. He describes the after-effect as follows: "Bei Anwendung des rothen Glases erscheint als negatives Nachbild eine helle rothe Scheibe auf dunkel grünem Grunde. Hierin liegt nichts Auffallendes und dieser Erfolg würde sich nach Analogie der Versuche von Fechner erklären lassen, auch ohne dass man eine Nachwirkung der inducirten Farbe voraussetze. Wende ich aber das grüne Glas an, so habe ich von der dunklen Scheibe ebenfalls ein helles rothes Nachbild und der Grund ist Schwarz, oder wenigstens so dunkel, dass ich seine Farbe nicht mit Sicherheit habe unterscheiden können. Hier hat also das inducirte Grün Roth hervorgebracht, während das inducirende gleichzeitig kein deutlich gefärbtes Nachbild erzeugte, In derselben Weise zeigte sich mir bei Anwendung des violetten Glases das negative Nachbild als eine gelbgrüne Scheibe auf schwarzem Grunde." In two cases here Brücke apparently has the positive excitation induced across the black disc, and in two cases the negative excitation. But since he does not make induction apply to the negative excitation, as has been done later, he does not explain this case as after-image of contrast, but makes it instead analogous to the phenomenon described by Fechner.

² Aubert (*Pogg. Ann.*, 1862, CXVI., pp. 249-279) says on p. 259: "Ausserdem ist es aber auffallend dass der simultane Contrast selbst noch einen successiven Contrast hervorruft, indem die durch den simultanen Contrast complementär gefärbten weissen Quadrate noch einmal complementäre Nachbilder hervorrufen, so dass jene Quadrate im Nachbilde dieselbe Farbe, nur sehr bedeutend abgeschwächt haben wie der Grund." Aubert observed white squares on a colored ground. In the positive sensation the squares took on a tinge of color complementary to the background, and in the after-image of the same color as the background. That is, a white square on a red background appeared greenish in the stimulus and red in the after-image. He says: "Besonders schön und mit einem eigenthümlichen Glanze erschienen die Nachbilder der weissen Quadrate auf dem blauen Streifen."

³ Brücke applies the term induction to the positive excitation only.

1878.¹ Hering worked with achromatic sensation alone. He also called the phenomenon an after-image of contrast sensation,² and upon his observations based his arguments against Helmholtz's theory of contrast. Continuing the discussion, the experiments were extended to color sensations by Ebbinghaus³ who considered the phenomenon a combination both of after-image of contrast and of contrast induced by an after-image.

The following form of experiment was adapted by us from Ebbinghaus. Squares 20×20 cm. of red, green, blue, and yellow Hering papers were fastened upon neutral gray backgrounds. Passing vertically through the center of these squares, gray strips 2×20 cm. of Hering papers numbers 8, 24, 2, 41, respectively, were pasted. The after-effect of stimulation by this combination is a square of a color complementary to the color of the stimulus square, traversed by a strip of the same color as the stimulus square. The red square, for example, gives a green square traversed by a strongly saturated

¹ Hering, E., 'Zur Lehre vom Lichtsinn,' Wien, 1878, pp. 5-18.

² On pp. 5-18 Hering describes experimental conditions similar to those described by Purkinje. Here he calls the phenomenon successive light induction. On pp. 24-29 he describes slightly different experimental conditions. Two dark gray strips of the same brightness, 3 to 4 cm. long and .5 cm. broad, are fastened parallel to each other 2 cm. apart, one upon a white and the other upon a black ground. A fixation-point is taken on the boundary between the white and black backgrounds midway between the strips. By contrast the strip on the white ground looks darker than the strip on the black ground. When an after-image of the strips, the one lightened, the other darkened by contrast, is obtained, their brightness values are reversed, and a still greater brightness difference between them is found. This difference toward black on one hand, and toward white on the other, Hering calls an after-image effect of the brightness contrast induced in the stimulus. The phenomena obtained by these two sets of conditions are in every sense identical. One can scarcely see a reason for the separate treatment they have received by Hering.

³ Ebbinghaus (*Grundzüge der Psychologie*, Erster Band, p. 239) says: "Man lege zwei mässig grosse Blätter z. B. von sattgrüner Farbe so auf einen grauen Grund, dass nur ein schmaler, etwa 5 mm. breiter horizontaler Streifen zwischen ihnen freibleibt, und lasse diesen von einer unbefangenen Person eine Weile fixieren. Dann lasse man sie das Nachbild auf einem etwas unregelmässig geformten Grunde entwerfen, z. B. auf dem Fensterkreuz, und frage, was sie sehe. Man wird so gut wie ausnahmslos die Antwort erhalten: 'einem grünen Streifen.' Der objektiv völlig neutrale Streifen hat durch die zweimalige Kontrastwirkung (im Vor- und Nachbilde), die sich von einer ausgedehnten Umgebung auf seine schmale Fläche konzentriert, eine so intensive Färbung bekommen, dass er sofort die Aufmerksamkeit auf sich zieht, während die röthliche Nachbildfärbung seiner Nachbarschaft bei den Unregelmässigkeiten der reagierenden Fläche in der Regel gar nicht beachtet wird."

red strip; the green square, a red square traversed by a green strip. Now if the color of the strip is an after-effect of a previously induced contrast, we have a strongly saturated, long-enduring after-image of an unsensed stimulus, for the brightness opposition of the gray strip to the inducing color, and the rather intensive illumination under which we worked, both combined to inhibit all contrast color in the stimulus. At this stage of the work we do not feel prepared to take positive ground on the question of explanation, but have the following evidence to offer that the Brücke interpretation is correct.

i. Evidence that the Color in the Strip is an After-Image of a Previous Contrast Sensation, rather than Contrast in the After-Image

(a) In the after-effect, the strip and square apparently develop, fluctuate, and die away independently of each other; the strip frequently develops before the square, especially if the stimulation has been very short; it invariably lasts longer than the square, returning several times after the square has finally disappeared; and in fluctuating, the two figures behave much as two after-images are observed to do, so far removed from each other as to be wholly without the sphere of reciprocal influence. The strip is frequently present when the square has disappeared, and vice versa. It rarely happens that their phases coincide, and when they do, the connection is obviously a chance one.

Records on this and the following points were taken from a number of observers, both experienced and inexperienced. The results given in the following tables are typical. The work was done in a large optics room, lighted on one side by a bank of windows extending nearly to the ceiling. The observer, head in rest, was seated in front of these windows so that the light coming from above and either side fell uniformly upon the projection-field of engine-gray cardboard, 1 meter distant. The time of stimulation, unless otherwise stated, was 30 seconds, and the unit of record was one second. The recording apparatus used throughout consisted of a Ludwig-Baltzar kymograph; a double electro-magnetic recorder, and two con-

tact keys, one for strip and one for square; a Jacquet chronograph set to seconds; and a lamp rheostat to reduce the current from the lighting circuit.

TABLE V

C. SHOWING THE INDEPENDENT PHASES OF VISIBILITY AND INVISIBILITY OF SQUARE AND STRIP

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20 cm. . . .	8	5	6.2	56	7.1	57	113
Gray No. 8, 2×20..	15	6	5	89.5	4	60	149.5
Green, 20×20	2	6	5	15	3.8	7.5	22.5
Gray No. 24, 2×20..	6	7	4.6	32	3.7	22	54
Yellow, 20×20	3	17	8	32	11	33	65
Gray No. 41, 2×20..	8	18	6.4	58	2.4	19	77
Blue, 20×20	4	12	6.5	32.5	5	20	52.5
Gray No. 2, 2×20..	9	11	6.1	61	3.7	33	94

TABLE VI

OBSERVER B

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20 cm. . . .	11	12	8.5	102	4	44.5	146.5
Gray No. 8, 2×20..	18	9.5	4.2	79	4	72	151
Green, 20×20	4	5	3.1	15.5	4.1	16.5	32
Gray No. 24, 2×20..	6	7	4.4	30.5	3.8	22.5	53
Yellow, 20×20	3	3.5	3.1	12.5	7.5	22.5	35
Gray No. 41, 2×20..	7	3	3.1	25	3.3	23	48
Blue, 20×20	6	13	4.1	28.5	7.3	44	72.5
Gray No. 2, 2×20..	11	3	3.6	43	3.3	36	79

TABLE VII

OBSERVER R

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20 cm. . . .	3	5	4.8	19	10.6	32	51
Gray No. 8, 2×20..	7	5	3.5	28	3.3	23	51
Green, 20×20	3	2	6.2	25	4	12	37
Gray No. 14, 2×20..	5	7	5.3	32	3.6	18	50
Yellow, 20×20	2	12	7.7	23	9.5	19	42
Gray No. 41, 2×20..	7	13	5.5	44	2.3	16	60
Blue, 20×20	3	22	9.8	39	4.3	13	52
Gray No. 2, 2×20..	10	7	4.2	46	3.1	31	77

(b) The mutual independence of strip and square can be further indicated by a method of concomitant variations. That is, the strip can be made to fluctuate less and last longer without any corresponding change in the fluctuation and duration of the square. And conversely, the square, or rather what in this variation corresponds to it, can be made to change its duration and rate of fluctuation, without any corresponding change in the fluctuation and duration of the strip. Both of these variations are based upon the effect of the arrangement relative to the direction of greatest involuntary eye-movement, upon the fluctuation and duration of a strip after-image. If the observer has more eye-movement in the horizontal than in the vertical, a strip after-image with its greater dimension in the vertical will fluctuate more and last a shorter time than one of the inverse arrangement. It may be stated as a law¹ that whenever the direction of greatest eye-movement is along the shorter dimension of the after-image, the maximal fluctuation and minimal duration is attained for that form of after-image.

Thus, to vary the duration and rate of fluctuation of the strip without changing them in the square, we need only to arrange the stimulus so that the longer dimension of the strip is first in the vertical and then in the horizontal. This rotation of the stimulus 90° will obviously have no effect upon the duration and rate of fluctuation of the after-image of the square, since both of its dimensions are equal. If we wish to make the converse variation, *i. e.*, change the duration and rate of fluctuation of the outer figure without changing them for the inner, we shall obviously have to make the outer figure a strip and the inner a small square. Then by rotating the stimulus 90° we shall increase or decrease the duration and rate of fluctuation of the outer figure, depending upon whether its shorter dimension is in the vertical or horizontal, while the duration and rate of fluctuation for the inner figure will not be affected.

(c) The Brücke interpretation seems also to receive negative support from the following fact. When one observes the

¹ Ferree, C. E., 'Intermittence of Minimal Visual Sensations,' *Amer. Journ. of Psychol.*, 1908, XIX., pp. 101-103. For explanation of this phenomenon see same reference, pp. 126-127.

TABLE VIII

C. SHOWING BY METHOD OF CONCOMITANT VARIATIONS A DECREASE IN FLUCTUATION AND AN INCREASE IN DURATION OF THE STRIP WITH NO SIGNIFICANT CHANGE IN THE PHASES OF THE SQUARE

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×20 cm.	3	25	15.3	61	5.7	17	78
Gray No. 2, 2×20 (vertical)	11	12	6.8	81	3.3	36	117
Blue, 20×20	2	48	20.6	62	5.8	11.5	73.5
Gray No. 2, 2×20 (horizontal)	9	11	9.4	94	4.3	39	133

TABLE IX

OBSERVER B

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×20	7	6	6.2	50	3.9	27	77
Gray No. 2, 2×20 (vertical)	13	4	4.1	57	2.2	29	86
Blue, 20×20	10	13	4.4	48	2.4	24	72
Gray No. 2, 2×20 (horizontal)	9	5	7	70	2.9	26	96

TABLE X

OBSERVER R

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×20	3	17	7.5	30	5	15	45
Gray No. 2, 2×20 (vertical)	7	7	4.4	35	2.1	15	50
Blue, 20×20	3	14	7.8	31	3.5	14	45
Gray No. 2, 2×20 (horizontal)	3	14	10.5	42	3.3	10	52

TABLE XI

C. SHOWING BY METHOD OF CONCOMITANT VARIATIONS A DECREASE IN FLUCTUATION AND AN INCREASE IN THE DURATION OF THE SQUARE WITH NO SIGNIFICANT CHANGE IN THE PHASES OF STRIP

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×.5 (vertical)	9	9	4.3	43	1.5	14	57
Gray No. 2, .5×.5	0	9	9	9			9
Blue, 20×.5 (horizontal)	5	15	9.7	58	2.4	12	70
Gray No. 2, .5×.5	0	7	7	7			7

TABLE XII

OBSERVER B

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×.5 (vertical)	8	6	3.3	30	2.3	18	48
Gray No. 2, .5×.5	0	7	7	7			7
Blue, 20×.5	4	10	9	45	2.5	10	55
Gray No. 2, .5×.5	0	8	8	8			8

TABLE XIII

OBSERVER R

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Blue, 20×.5	7	5.5	4	32	2	14	46
Gray No. 2, .5×.5	0	5	5	5			5
Blue, 20×.5 (horizontal)	3	43	17	68	1	3	71
Gray No. 2, .5×.5	0	10	10	10			10

stimulus through tissue-paper or under decreased illumination, the relative duration of strip to square in the after-effect is very greatly increased. This should not take place if a color in the strip after-image is induced by the color in the after-image square. The ratio should remain constant or approximately so, *i. e.*, since the intensity of the after-image square has been reduced by weakening the color of the stimulus square by tissue paper, a corresponding weakening would be expected in the color induced in the strip. The observation thus seems to furnish a negative indication that the after-image interpretation is correct. Relative to this observation, however, two points need to be taken into account. (1) An inspection of the tables shows that although there is an increase in the ratio of duration of strip to square, there is an actual decrease in the absolute duration of the strip. This might be supposed to indicate a tendency for the strip to vary with the square and thus to favor the contrast interpretation; but the increase of relative duration is too great for this to be probable. Besides, the decrease in absolute duration can be readily accounted for from the other side by a decreased retinal induction in the

stimulus due to the decreased saturation of the square. (2) The second point is quite aside from differential evidence as between the Brücke and Ebbinghaus interpretations. When the stimulus was observed through tissue-paper or under decreased illumination, considerable contrast color developed in the stimulus, where before there had been none, yet the after-image was less than in the former case. This seems to indicate the following. (a) The contrast sensation is only an equivocal index of the amount of excitation set up on the retina by a neighboring surface. This excitation may under one set of conditions arouse an intensive sensation, and under other conditions be equally strong, at least as far as after-effect goes, and excite no sensation. (b) Brightness opposition inhibits only the contrast sensation. It apparently does not inhibit the corresponding retinal induction due to the neighboring surface, at least not its power to give after-effects. That is, the brightness opposition between the square and strip in the stimulus was greater when the tissue-paper was not used and yet the strongest after-image of the contrast excitation was obtained in this case. These suggestions are thrown out merely tentatively and are meant to apply only within the bounds of the evidence offered.

Since the results are similar for both the tissue-paper device and the decrease of illumination, tables will be given only for the former.

TABLE XIV

C. SHOWING THE PHASES OF INVISIBILITY AND VISIBILITY OF STRIP AND SQUARE AND THEIR RELATIVE DURATIONS, OBSERVED UNDER TISSUE PAPER

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20	0	3	3	3			3
Gray No. 8, 2×20 . .	3	4	2.5	10	3	9	19
Green, 20×20	0	7	7	7			7
Gray No. 24, 2×20 .	2	5	3.3	10	6.5	13	23
Yellow, 20×20	1	8	4.8	9.5	3	3	12.5
Gray No. 41, 2×20 .	4	8	3.8	19	3.6	14.5	33.5
Blue, 20×20	1	5	6	12	6	6	18
Gray No. 2, 2×20 .	4	3	2.3	14	2.5	10	24

TABLE XV

OBSERVER B

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20.	0	2	2	2			2
Gray No. 8, 2×20. .	3	1	1.9	7.5	4.8	14.5	22
Green, 20×20.	0	7	7	7			7
Gray No. 14, 2×20. .	2	4	4	12	5.8	11.5	23.5
Yellow, 20×20.	0	4.5	4.5	4.5			4.5
Gray No. 41, 2×20. .	3	4	3.1	12.5	4	12	24.5
Blue, 20×20.	1	3	2.5	5	7	7	12
Gray No. 2, 2×20. .	7	4	3.5	28	3.1	22	50

TABLE XVI

OBSERVER R

Stimulus	No. of Fluctuations	1st Vis.	Av. Vis.	Total Vis.	Av. Invis.	Total Invis.	Vis. + Invis.
Red, 20×20.	0	3	3	3			3
Gray No. 8, 2×20. .	3	3	2	8	3.3	10	18
Green, 20×20.	0	8	8	8			8
Gray No. 14, 2×20. .	3	4	3.5	14	3.3	10	24
Yellow, 20×20.	1	6	4.5	9	2	2	11
Gray No. 41, 2×20. .	3	5	4.5	18	4	12	30
Blue, 20×20.	1	5	4	8	5	5	13
Gray No. 32, 2×20. .	4	5	4.6	23	3	12	35

ii. But if a Contrast Effect, Evidence that it May Take Place when the Inducing Color is Unsensed

As already stated, the strip frequently develops before the square; it invariably lasts longer than the square; returning several times after the square has finally disappeared; and in fluctuating its phases rarely coincide with those of the square, *i. e.*, it is frequently visible when the square is invisible, and conversely.

Thus it is immaterial for our thesis which interpretation be given to the phenomenon. For (*a*) if the after-color in the strip be a contrast sensation, our results show that it may be set up when the inducing excitation is not directly conditioning sensation; and (*b*) if it be an after-image sensation, they show that it may be aroused by a previous excitation which did not itself directly give rise to sensation.

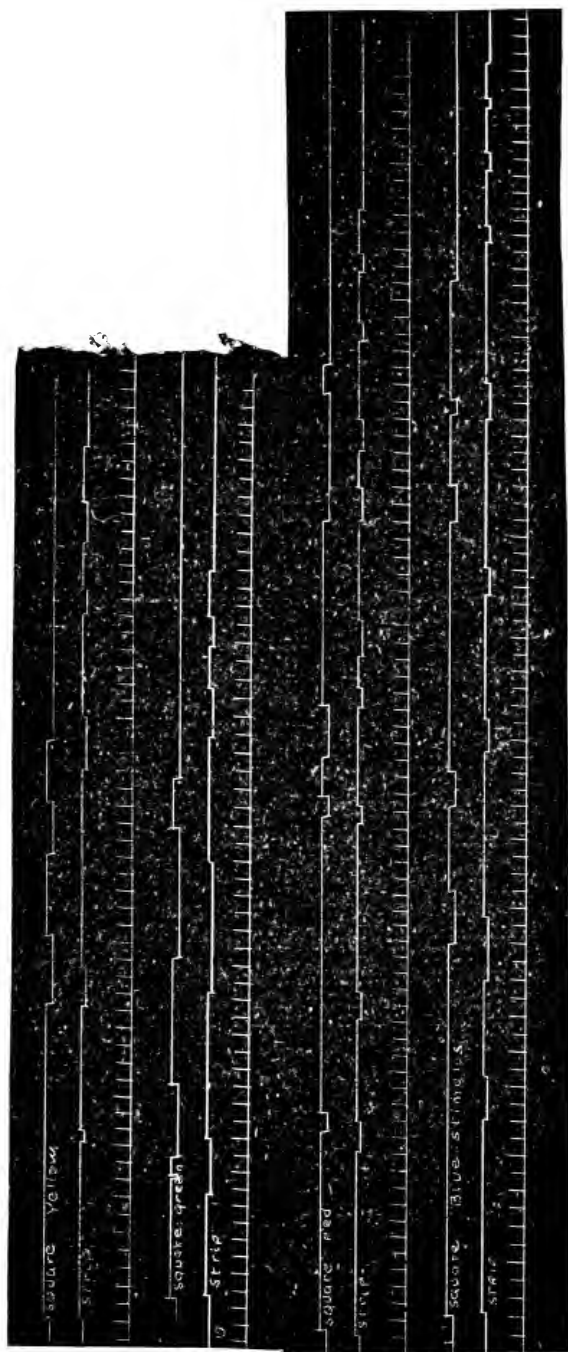


FIG. 1. (Observer R.) Records showing the fluctuations and duration of strip and square.

III. EXPLANATION

A later paper will contain a history of the observations on the effect of brightness changes, general and local, upon color phenomena, beginning with Purkinje.¹ Purkinje's observations cover the following points. (1) The relative difference in the brightness values of the spectral colors at full and decreased illumination. (2) The difference in the effect of change in brightness upon the saturation of colors. (3) The changes in color-tone produced by changes in brightness.

After-Image

The explanation of the possibility of getting color as an after-image from a stimulus in which no color can be sensed rests in general with the second point of Purkinje's observations; namely, the difference in the effect of change in the brightness of different colors upon their saturation. In every case in which a colored after-image was obtained from a colorless stimulus, it was gotten at a degree of brightness which worked against color saturation in the stimulus and relatively favored it in the after-image. Take, for example, the case of central vision. By the first method the influence of the brightness factor was introduced by means of a decrease in the general illumination. Yellow and red and orange lose their saturation at an illumination that permits of a supraliminal saturation of blue and green. The case, then, is simple. There was retinal excitation in the cases of red, yellow, and orange, but it was obscured for sensation by the brightness factor. The after-effect of this excitation, however, was not obscured for sensation. It was relatively favored, and, therefore, gave the after-images which were observed. There is nothing new or strange in principle about this phenomenon. The foregoing results show that it depends entirely upon the effect of the brightness changes in a color upon its saturation. These effects were observed and reported as far back as the time of Purkinje, and have been discussed sporadically in the literature from that time to this. By the second method the unfavorable

¹ Purkinje, 'Beobachtungen und Versuche zur Physiologie der Sinne,' 1823, I., p. 109.

brightness quality was added to the stimulus color by objective mixing, contrast, or after-image; and the favorable brightness quality was added to the after-image by means of the projection field. The after-image method was found to be the most effective for adding the unfavorable brightness quality to the colored stimulus because by means of it (a) the amount of colored light coming to the eye is not reduced as it is by the method of objective mixing; and (b) the unfavorable brightness quality added to the stimulus color is not added to the after-image color also, as is done under the conditions of the experiment by the method of contrast.

For the after-image in peripheral vision, we have a slightly different case. The peripheral retina differs from the central with regard to the effect of change in brightness upon both the saturation and the quality of colors. With regard to saturation, we have in general merely an exaggeration of the condition found in the central retina, *i. e.*, brightness changes produce greater difference in effect in the case of the different colors. With regard to color tone, the change is not in the same direction in every case as it is in central vision, *i. e.*, in central vision at full illumination. In this paper, however, we are concerned with the effects upon saturation alone. Moreover, under a given set of conditions more of the brightness quality can be added as after-image and contrast in this region of the peripheral retina than in the central retina because of the increased sensitivity of the former to achromatic after-image and contrast. We have then in these regards especially favorable conditions in the peripheral retina for obscuring stimulus color by brightness changes, and for relatively favoring the development of the after-image. We have as an additional factor the enhanced sensitivity of the peripheral retina to adaptation and after-image effects. It adapts very rapidly to color stimuli and responds quickly with a vivid after-image of short almost momentary duration, often described as a vivid flash of color. All of these factors make it comparatively easy to get after-images of unsensed stimuli in peripheral vision, the only fact relative to our problem that needs to be explained.

Contrast

It was found to be especially easy to arouse green, blue-green, and blue as contrast sensations when their inducing stimuli do not directly excite a sensation of color. Two factors are involved in this result. (1) A decrease of the illumination obscures red, orange, and yellow before it obscures their contrast colors, green, blue-green, and blue. Hence, induction and the effect of decrease of illumination upon it aside, there is reason in the nature of the color processes themselves why red, for example, should not be sensed when its contrast color, green, is sensed. But (2), in addition to this, decrease of illumination enormously enhances the induction of the contrast color, this effect being greater for green, blue, and blue-green than for their complementary colors red, yellow, and orange.

The Purkinje-Brücke Phenomenon

Until a final decision has been made between the after-image and the contrast interpretations, the Purkinje-Brücke phenomenon presents a two-fold problem. From the side of the after-image interpretation it must be explained how an after-effect so intensive and of such long duration can be obtained from a stimulus of so little apparent intensity; *e. g.*, in our form of the experiment, no color at all could be sensed in the strip. From the side of the contrast interpretation, it must be shown how contrast color can be gotten in the after-effect of the strip when the square is not in sensation; *i. e.*, before the square appears, in the invisibility phase of its intermittence, and after its final disappearance.

At this stage of the work, an explanation will not be attempted. From the Brücke side, however, it may be pointed out that evidence has already been given that color in the contrast sensation is only an equivocal index of the actual amount of the corresponding retinal color excitation. Also, that, while this induced excitation may arouse a strong sensation, a weak sensation, or even none at all, depending upon concomitant brightness conditions, contour, etc., nevertheless, in all of these cases, it gives rise to after-sensations of color, and to the most intensive in the cases we used, when no color was sensed in the

stimulus. In fact, it was just to take advantage of this point that our method was devised. We introduced brightness opposition between strip and inducing color to prevent the induced excitation from arousing a sensation of color, knowing that its power to condition color in the after-image was not diminished thereby, providing the brightness conditions were favorable for the development of the color. The brightness conditions were made tolerably favorable by choosing a shade of gray for the stimulus strip whose after-image was approximately the brightness of the after-image color. From the side of the Ebbinghaus interpretation, the writers have not at present even a plausible suggestion to offer in explanation. However, lack of explanation of this phenomenon does not limit its confirmation of our thesis that stimuli in which no color is sensed may arouse after-image and contrast sensations in which color is sensed.

We wish to state in conclusion that our chief interest in the problem has been its share in the broader problem presented by the Purkinje observations. We do not think that sufficient attention has been given to the second and third of these observations and the light they may throw on color theory. Up to this time, theory has practically ignored the effect of brightness changes upon the saturation and quality of color sensation. These effects seem to argue a functional connection between chromatic and achromatic processes which should not be disregarded.



AN OPTICS-ROOM AND A METHOD OF STANDARDIZING ITS ILLUMINATION

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I. INTRODUCTION

In a previous article¹ the statement was made by the writers that all comparative estimates of the sensitivity of the retina to color (limens or limits) should be made in daylight instead of in the dark-room. This is to eliminate the influence of the field surrounding the colored stimulus, and of the preëxposure. When the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness,² the induction takes place in different amounts for the different colors. This white, in proportion to its amount, reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. To eliminate this twofold unequal action, the surrounding field should be made in each case of the brightness of the color to be used. This can be done by working in a light-room of constant intensity of illumination and by making the surrounding field of a gray paper of the brightness of the stimulus color. In order to accomplish this and at the same time be able to work in any meridian of the retina we choose, we have constructed a special piece of apparatus which we call a rotary campimeter.³ The influence of preëxposure is even more important than of sur-

¹ Ferree and Rand, 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Journ. of Psychol.*, 1912, XXIII., p. 331.

² In a later paper, one of the writers (Rand) will show that it is of no advantage to equate in brightness in determining the limits of color sensitivity, and that harm results in so many ways from the attempt to equate, that it is doubtful whether it should be done even in determining the limens of color in the more sensitive parts of the retina.

³ See C. E. Ferree, 'Description of a Rotary Campimeter,' *Amer. Journ. of Psychol.*, 1912, XXIII., pp. 449-453.

rounding field. If the preëxposure is to black, white is added as after-image to the stimulus color. The effect of a black preëxposure upon the stimulus color is greater than the effect of a black surrounding field because more white is added as after-image of preëxposure than is induced by contrast from the surrounding field. This effect also can be eliminated only by working in a light-room of constant intensity of illumination and choosing as preëxposure a gray of the brightness of the color to be used.

Standardization for either one of these factors, however, can be accomplished for one degree of illumination only.¹ As the general illumination changes, the relation of the brightness of the preëxposure and of the surrounding field to the brightness of the colored stimulus changes. It is obvious, then, that if standardization is to be accomplished with regard to the influence of either of these factors, some means must be devised of maintaining the general illumination of the retina constant. No satisfactory method has as yet been obtained for keeping the illumination of a room by daylight constant. To keep it constant presupposes what has not as yet been provided, namely, a sensitive means of measurement. Constancy may be approximated by artificial illumination, but no artificial source of light has yet been devised which gives a light that approaches average daylight² sufficiently closely in composition to warrant its use in color work. Of the various sources of light the Moore Tube comes nearest to doing this, but spectrophotometric and colorimetric determinations show that the light from it contains an excess of blue,³ and, therefore, although it

¹ When the colored light used to stimulate the retina is independent of the general illumination, *e. g.*, when it is obtained from the spectrum, from monochromatic sources, or from standard filters, these two factors alone will modify the result of the color observation. If, however, light reflected from a pigment surface be used as stimulus, a change in the illumination will in addition change the amount of colored light coming to the eye.

² For results of measurements of the color values of average daylight, see Nichols, E. L., *Transactions of the Illuminating Engineering Society*, 1908, III., p. 301. Ives, H. E., 'The Daylight Efficiency of Artificial Illuminants,' *The Illuminating Engineer*, 1909, IV., pp. 434-442; and 'Color Measurements of Illuminants,' *Transactions of the Illuminating Engineering Society*, 1910, V., pp. 189-207.

³ See Ives, H. E., 'Color Measurements of Illuminants,' *Transactions of the Illuminating Engineering Society*, 1910, V., p. 206; and Rosa, E. B. quoted by Moore,

has been adopted by various textile concerns for use in color matching, its substitution for daylight can scarcely be recommended for the more exact requirements of color optics. Ives and Luckiesh¹ attack the problem of producing artificial daylight from another side. By their subtraction method they claim to have gotten the closest approximation to average daylight yet attained. They aim to cut out by absorbing screens the excess of red and yellow in artificial light due to the comparatively low temperature of artificial illuminants. Tungsten lamps are used by them as the source of light, and two kinds of commercial glass approximating in their absorptive action cobalt blue and signal green are used as screens. In order to correct for the pronounced band of yellow-green transmitted by the cobalt blue, a film of gelatine dyed with rozaecine is also used. Although according to comparative measurements made by Ives and Luckiesh the light thus gotten is the closest approximation to average daylight yet obtained, still it shows a deficiency of 15 per cent. in the green and about 25 per cent. in the blue. Moreover the spectrum of this light does not show the brightness distribution of the spectrum by daylight. Since the absorbing screens cut down the light emitted by the tungsten lamp to 15 per cent. of its original intensity, the spectrum of the light finally given out shows the brightness distribution characteristic of lights of low intensity. We seem thus compelled either to give up the investigation of the color sensitivity of the retina for daylight illumination, or to devise some means of keeping this illumination constant. At an early stage of our work of standardizing the factors extraneous to the source of light, we were compelled to take into account the influence of the changes in the illumination of the visual field upon the color observation. The changes of illumination that took place from day to day, the progressive changes during the day, and the many sudden changes even in the course of an hour, rendered any constancy, or close reproduction of results entirely out of the question.

D. McF., 'A Standard for Color Values,' *Transactions of the Illuminating Engineering Society*, 1910, IV., p. 224.

¹ Ives, H. E., and Luckiesh, M., 'Subtractive Production of Artificial Daylight,' *Electrical World*, 1911, LVII., pp. 1092-1094.

In order to obtain a standard illumination, two things are necessary: (a) A means of controlling the illumination must be provided, which is sufficiently sensitive to cause small changes. (b) A method of measuring the illumination produced has to be devised; at least, a means must be secured for determining when an illumination has been obtained that is equal to a given preceding illumination. It is the purpose of this paper to describe an optics-room provided with means of control which we have found adequate to meet the above requirements; and to state a method of identifying and reproducing any given illumination of this room.

II. DESCRIPTION OF OPTICS-ROOM

The dimensions of the room are $12\frac{1}{2} \times 10$ ft. It is situated on the upper floor of an isolated building and is lighted by a skylight $8 \times 7\frac{1}{2}$ ft. Beneath the skylight two diffusion sashes, $4 \times 7\frac{1}{2}$ ft., are swung on hinges so that they can be raised or lowered as desired. The framework of these sashes is made of light-weight iron. For convenience of local control of illumination, if needed, each sash is divided into four units by means of cross-pieces. The sashes are filled with double-strength glass ground on one side, so adjusted to the frame that they can be removed easily for cleaning or for the substitution of some other kind of glass in case that is desired. This glass diffuses the light so effectively that local shadows cast by the cross-pieces in the framework of the skylight are completely eliminated, while the sudden changes of illumination produced by the passage of the sun behind a cloud are reduced to a minimum. This diffusion seems to have the further advantage of reducing the yellowness of direct sunlight below the limen of sensation. At least, when working under the sash, the observer never judged a gray exposed through the campimeter opening as yellow under any local conditions, as frequently happened when working under direct sunlight.

The room is planned also so that small changes of illumination can be produced, ranging from the intensive illumination of a south-exposure skylight to the blackness of a moderately good dark-room. Two provisions are made for this. (1) The

diffusion-sashes are made so that any or all of the panes of ground glass can be quickly and easily taken from the sash, and anything can be substituted that is desired; or the illumination can be varied by placing layers of tissue paper above the glass. (2) The room is provided with two curtains mounted on heavy spring rollers. One is a white curtain made of thin muslin; the other is a black light-proof curtain so mounted that, when drawn, its edges are deeply enclosed in light-proof boxing extending along the four walls of the room. One or both of these curtains can be drawn any distance that is desired, and the illumination can thus be changed gradually from a very intensive brightness to a fairly good blackness. To aid in getting dark-room effects, the doors of the room are carefully boxed and curtained. One requirement of a perfect dark-room, however, is lacking, namely, the walls and floor of the room are painted white. This is because it is of advantage in the light-room work, and because complete blackness is not needed in the type of work for which the room is devised.

III. METHOD OF STANDARDIZING

As stated earlier in our paper, no satisfactory means of determining the amount of daylight illumination in a room has been provided by the physicist, so there is little hope at this time of solving the problem from that side. The brightness induction of the peripheral retina, however, has been found by us to be extremely sensitive to changes in the general illumination. This phenomenon seems to provide us with a sensitive measure of these changes while, at the same time, it represents the combined effects for sensation of the principal subjective factors that might vary from day to day.¹ To apply the method in its most sensitive form, the inductive power of white was chosen because it is the most strongly affected by illumination changes. For example, when No. 14 Hering gray was used as stimulus and white as campimeter screen, a noticeable change was produced in the induction when the white curtain of the optics-room was pulled forward 1 cm.²

¹ This means of identifying the illumination of a room was devised by Rand.

² The sensitivity of this method of detecting changes in the general illumination was compared with the sensitivity of the Sharpe-Millar portable photometer. In

from a position in which its edge was directly above the long axis of the campimeter. This caused a change in the illumination of the room so small that it could not be directly sensed. Further, at 11 o'clock in the morning of a bright day in September, when a point at 25° on the nasal meridian was stimulated, one of the writers (Rand) reported that the white screen induced black across the stimulus No. 14 gray to an amount that caused it to equal in brightness 107° of black and 253° of No. 14 gray; at 2 o'clock of the same day the induction was increased until the No. 14 gray matched 150° of black and 210° of the gray; at 4 o'clock of the same day the No. 14 gray matched 180° of black and 180° of the gray.¹ Working at 25° in the temporal meridian, this observer reported at different times during one day and on different days, the wide variations shown by the following figures: 283° of black, 225° , 145° , 190° , 238° , etc. Another observer (Miss Campbell) reported less induction, but her variations from time to time were equally great. At 25° in the temporal meridian, she found at different

this photometer one of the comparison fields is illuminated by the light of the room and the other by a standard tungsten lamp enclosed in the photometer box. When the room is illuminated by daylight, the field receiving the light of the room is seen as white while the field lighted by the tungsten lamp appears as a saturated orange. The difference in color between the two fields renders the photometric judgment difficult and makes the instrument very insensitive for daylight tests. For example, our tests showed that by the method for identifying an illumination described in the text, a change in illumination could be detected which was produced by drawing the white curtain 1 cm. from a position in which its edge was directly above the long axis of the campimeter. But with the receiving surface of the portable photometer in precisely the same position as the stimulus screen of the campimeter, the edge of the curtain had to be moved 11.3 cm. in order that the change of illumination might be detected. Moreover, this amount of change could be detected only in case the photometric field was continuously observed while the curtain was being drawn, in which case the comparison field was observed to be slightly darkened. The judgment was made, then, in terms of a just noticeably different brightness of the field which was illuminated by the daylight, rather than in terms of a disturbance in the brightness-equality of the two fields. When, on the other hand, the judgment was made in terms of a just noticeable disturbance in the equality of the two fields, as the judgment would have to be made if the photometer were to be employed for the reproduction of any former illumination taken as standard, the curtain had to be drawn 44.2 cm. before the change could be detected. This j. n. d. represents an amount of illumination equal to 2.5 foot-candles.

¹ This increase in the inductive action of the screen caused by the decrease in illumination, was accompanied by a shrinkage of the zones sensitive to color covering an area of 4° to 6° .

times 80° of black, 103° , 160° , 175° , etc. After a careful study of the phenomenon with different screens and with different backgrounds, the inductive action of the white screen upon a stimulus of No. 14 Hering gray, at 25° in the temporal meridian, was found to provide the best means of detecting changes in the illumination of the optics-room. At this point on the retina, the induction was by no means minimal, nor was it sufficiently great to cause the medium gray chosen for our stimulus to appear too dark to give a small j. n. d. of sensation. Having thus provided ourselves with a means of producing small changes of illumination and a method of detecting them, we had in order to complete our work but to choose an illumination for each observer, which could be used as standard. Since we wished to work on both light days and days of medium darkness, an average had to be chosen as our standard from the measurements obtained on a number of days ranging from light to dark, so that on bright days, the room could be darkened, and on dark days it could be lightened until this value was obtained. For observer *A* (Rand) an illumination was selected which caused an induction of black across no. 14 gray stimulus viewed at 25° in the temporal meridian to an amount which caused the gray stimulus to equal in brightness 210° of black and 150° of no. 14 gray; for observer *B* (Ferree) 180° of black and 180° of no. 14 gray; and for observer *C* (Campbell) 145° of black and 215° of no. 14 gray. The amount of black induction was identified in each case by means of a measuring-disc made up of sectors of black paper and no. 14 gray of the Hering series. This measuring-disc was carried by a motor and placed just behind the 25° point. The observer fixated the 25° point and compared the gray of the measuring-disc as seen in central vision with the gray of the stimulus seen 25° from the fovea. The sectors of the measuring-disc were then changed until the two grays were of equal brightness.

Previous to each series of observations the illumination of the room was changed until the amount of brightness induction was brought to the value chosen as standard. It was tested at intervals during the sitting and was readjusted when

necessary. Details of the method of doing this are as follows. When the white screen and the no. 14 gray stimulus had been put in place, the observer took his position and adjusted the fixation-knot in front of the motor for the 25° point on the temporal meridian. The measuring-disc set at the standard value was mounted on the motor. The observer reported whether the stimulus appeared lighter or darker than the measuring-disc, or of a brightness equal to it. If the judgment lighter or darker was given, the curtain was drawn one way, or the other until the stimulus accurately matched the measuring-disc in brightness.

This method not only gives a sensitive measure of the changes of illumination of the visual field and a successful means of standardizing the illumination of a room by daylight, but it has in addition advantages for work in psychological optics not possessed by an objective standardization, could that be successfully obtained. The problem of standardization includes more for the psychologist than it does for the physicist, for the former has variables to take into account in addition to the changes that may take place in the energy of the stimulus. Even though the illumination of the room be made objectively constant, we should expect variations in the response of the retina to this illumination because of its own changes from time to time. Brightness contrast, for example, might be expected to vary from sitting to sitting even when the stimulus conditions are kept absolutely constant. Two factors would be concerned in these variations: changes in the inducing power of the surrounding parts of the retina, and changes in the sensitivity of the local area. These changes would take place even when the usual precautions known to the experimenter in this field have been observed. Such precautions are commonly limited to fatigue, adaptation, etc. These precautions do not provide for the changes that occur in the retina from day to day. Moreover, they do not adequately guard against the variations to which they are intended to apply, for no precaution can adequately guard against a change in a factor, unless some measure of that factor be had. So far as the writers know, in these general

precautions intended to keep the state of the retina constant, no measure of the variable factor has been provided to test the adequacy of the method. The method proposed by us, however, is planned with this in view. It takes into account not only the objective, but the subjective variables, and reduces both to a constant. For example, when no. 14 gray surrounded by the white field is made equal to the measuring-disc composed of 210° of black and 150° of the no. 14 gray for observer *A*, it means that the observation may be begun with the assurance that the total result of all the factors—the illumination of the room, the local sensitivity of the retina, and the inductive action of the surrounding parts of the retina—is the same as in the preceding observation.

What has just been said should not be considered as more than a general statement of the application of the principles of the method. In actual practice a greater refinement of working may be attained. If, for example, one wishes to use a preëxposure differing in brightness from that of the colored stimulus, and doubts whether a test which covers only the local sensitivity of the retina and the inductive action of the surrounding parts is a sufficient check upon the after-image sensitivity, he may make his standard include the effect of the preëxposure he wishes to use. In short, if he does not consider adequate the more general test we have described, he may duplicate, in establishing his standard, any combination of brightness factors, due to preëxposure, brightness of screen, or what not, that he may wish to use in his experiment proper.

The test of a method is how well it works. The test of this method is that we shall be able closely to duplicate our results from sitting to sitting regardless of the changes in the outside illumination from day to day or from morning until afternoon. The method stands the test. Long series of observations in the peripheral retina show a very small M.V.—much less even than is shown in the ordinary color observations in the central retina, where, as compared with the peripheral retina, the factors extraneous to the stimulus exert little influence.

The following table has been compiled from a number of observations to show the variations in the results of color limens and color limits (*a*) when the general illumination was controlled according to the method described above, and (*b*) when no more precautions were observed than were used by previous investigators. In previous investigations of the color sensitivity of the peripheral retina, care has been taken to work only at the same hours of days that appeared equally bright, or, if on days of different brightness, to make a rough approximation of preceding illumination by means of curtains without using either a definite standard or means of measuring. For our work with the illumination controlled, the gray of the brightness of the color at the illumination selected as standard was used for the preëxposure and the campimeter screen. For the work without especial control of the illumination, the gray of the brightness of the color for one of the days selected as typical was used throughout for preëxposure and screen. This gave in the first case complete elimination of the effect of preëxposure and surrounding field, and in the second case elimination as complete as could be gotten without accurate control of the general illumination. Results are given in the table for blue and green only because the sensitivity to these colors is affected most by changes of illumination.

Stimulus	Illumination	Screen and Preëxposure	Variations of Limits on Different Days	Variation of Limens on Different Days
Green.....	Controlled.....	Gray No. 9	0°	0° ¹
	Uncontrolled.....	Gray No. 8	4°-6°	60°-82°
Blue.....	Controlled.....	Gray No. 33	0°	2°-3° ²
	Uncontrolled.....	Gray No. 32	4°-5°	18°-30°

¹ The limen for green was taken in both cases at 25° on the temporal retina.

² The limen for blue was taken in both cases at 40° on the temporal retina.

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THE EFFECT OF CHANGES IN THE GENERAL ILLUMINATION OF THE RETINA UPON ITS SENSITIVITY TO COLOR¹

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I. Introduction.

II. Historical.

III. Experimental.

- (1) Quantitative estimate of the influence of change of illumination upon the induction of brightness by the surrounding field.
- (2) The effects of these amounts of induction on the limits of color sensitivity.
- (3) The effect of these amounts of induction on the limens of color at different degrees of excentricity.
- (4) The influence of change of illumination upon the effect of the preëxposure on the limens and limits of color.

IV. Conclusion.

I. INTRODUCTION

It is the purpose of this paper to show the effect of changes in the intensity of the illumination of the field of vision upon the results of investigations which deal with the sensitivity of the retina to color.²

A method of standardizing the illumination of the field of vision was described in an earlier paper.³

II. HISTORICAL

The effect of the general illumination of the retina on color

¹ From the Bryn Mawr Psychological Laboratory.

² With regard to this effect two cases may be recognized: (1) When the colored light used to stimulate the retina is independent of the general illumination, *e. g.*, when it is obtained from the spectrum, from monochromatic sources, or from standard filters; and (2) when it is obtained by reflection from pigment surfaces. In the first case the effect is exerted in the following ways: (*a*) by changing the brightness relation of the preëxposure to the colored surface, (*b*) by changing the brightness relation of the surrounding field to the colored stimulus, (*c*) by altering the sensitivity of the retina to brightness after-image and contrast and thus changing the effect of the brightness of the preëxposure and of the surrounding field upon the sensitivity of the retina to the colored stimulus. To these effects is added in the second case a change in the amount of colored light coming to the eye.

³ Ferree and Rand, 'An Optics-room and a Method of Standardizing its Illumination,' *PSYCHOL. REV.*, 1912, XIX., pp. 364-373.

sensitivity has been recognized since the time of Purkinje and Aubert. It has been studied in some detail by a number of experimenters, among whom may be mentioned Kramer and Wolffberg. Both have shown that the sensation aroused by the colored stimulus is weakened by a reduction of the general illumination but neither has given a method of keeping the general illumination constant. Kramer's¹ purpose was to determine the sensitivity of the eye under different intensities of daylight and artificial illumination. His method was as follows. Stimuli, 4 mm. square, of blue, yellow, red, and green paper on a black background were used. The distance at which the stimulus had to be placed from the observer to be just recognized as colored was tested by sunlight and when the sky was obscured by clouds and for three intensities of each of the following sources of artificial illumination: candle-light, gas, petroleum, sodium, potassium, strontium, and calcium lights. His results show the following facts: (1) Red is seen at the greatest distance in all lights except calcium, in which case green is seen when placed farther away than red. The other colors are recognized in the order green, yellow, blue. (2) All the colors are recognized at a greater distance when seen by sunlight than when illumined by artificial light or the dull light from a clouded sky. (3) As the intensity of the artificial illumination is decreased, the colors must be placed nearer the eye to be recognized. In drawing his conclusions with regard to comparative sensitivity, Kramer ignored the white contrast which the black background induced across the stimuli. The induction across stimuli whose sizes were only 4 mm. square must have been considerable. It was, moreover, of different amounts in each case; because brightness contrast is greatest when there is maximal brightness opposition. The modification of the light colors, as a result of contrast induction, must, therefore, have been greater than that of the dark colors. Wolffberg's² interest was in the influence of gradual alterations of the general illumination on

¹ Kramer, J., 'Untersuchungen über die Abhängigkeit der Farbenempfindung von der Art und dem Grade der Beleuchtung,' Inaug.-Diss., Marburg, 1882.

² Wolffberg, 'Ueber die Prüfung des Lichtsinnes,' *A. f. O.*, 1887, XXXI., pp. 1-78.

the light and the color sensitivity of the central and of the peripheral retina. His room was illuminated by daylight entering through a window. Fifteen different degrees of illumination were produced by fastening from one to fifteen thicknesses of tissue-paper over the window. The illumination obtained when the window was uncovered was called 15/15; when covered with one thickness of tissue-paper, 14/15, etc. His method of determining the effect of variations of illumination upon the central retina was as follows: Pigment stimuli were placed at a standard distance of 5 meters from the observer, and the size of stimulus necessary to render it just visible in its true color was determined. In the peripheral retina, he investigated to what extent the limits of white and of colored stimuli were altered by reducing the illumination. In all his experiments, the stimuli were fastened on a black background. Wolffberg's results for the central retina are shown in the following table. The stimuli were circular in shape and of diameters given in columns 2, 3, 4, 5, and 6.

Illumination	Size of Red Stimulus	Size of Blue	Size of Green	Size of Yellow	Size of White
15/15	.5 mm.	3 mm.	3 mm.	1.5 mm.	.2 mm.
14/15	1.5	5	4	2	.5
13/15	2	6	6	4	1
12/15	2.5	12	12	4.5	2
11/15	3	20	20	5	2.5
.....
5/15	10	50	50	10	6

These results show that in the central retina a decrease of illumination has greater effect upon the sensation of color than upon the sensation of white. Wolffberg next tested the effect of a gradual decrease of illumination upon the limits of sensitivity to white and to the colors. He found that the extent of the visual field was not narrowed for white when the illumination was decreased to 1/15. The color limits, however, narrowed gradually when the illumination was decreased from 15/15 to 3/15. The narrowing was in no case more than 15°. The relative extents of the fields remained unaltered, *i. e.*, the order of size was in every case blue, red, and green.

Although special investigations have been conducted by Kramer, Wolffberg, and others to show the effect of changes in the general illumination upon color sensitivity, in general little if any precautions have been taken by earlier experimenters to prevent such changes when investigating color sensitivity. Either the experimenter has not considered the influence of the general illumination, or he has been satisfied to take the rough precaution to work only on bright days at stated hours. Ole Bull,¹ for example, commented at length on the factor of general illumination, but suggested no method for its standardization. He writes: "The amount and nature of the general illumination are of more significance in perimetrical observations than one is accustomed to consider. It must always be noted whether the sky is clear or cloudy, whether it rains or snows. The extreme limits of the visual field for mixed light undergo such wide fluctuations that it is of little value to establish an average limit on the basis of a number of measurements. Changing illumination, conditioned by the time of day and of year during which the work is carried on, as well as the locality in which it is undertaken, produce variations in the same stimulus large enough to cause differences of from 10° to 20° [in the limit of sensitivity]. Especially in the nasal parts of the retina does the illumination influence the color limits, while their position remains more constant in the temporal retina." Fernald,² however, did make some attempt to obtain a standard illumination. She arranged white curtains at the windows of her optics-room, which could be lowered on bright days and drawn on dark days. This rather crude method was used also by Thompson and Gordon.³ It is scarcely necessary to point out that the method lacks the first essential of standardization, namely, a means of measuring.

It is surprising that Wolffberg, as the logical corollary of his work, did not draw attention to the importance of standard-

¹ Ole Bull, 'Perimetrie,' Bonn, 1895, p. 8.

² Fernald, G. M., 'The Effect of the Brightness of Background on the Extent of the Color Fields and on the Color Tone in Peripheral Retina,' *PSYCHOL. REV.*, 1905, XII., p. 392.

³ Thompson and Gordon, 'A Study of After-images on the Peripheral Retina,' *PSYCHOL. REV.*, 1907, XIV., p. 122. r

izing the illumination of the visual field in all work on the color sensitivity of the retina, and show how it could be accomplished by a modification of his method of working. He already had at hand one of the essentials for standardizing, namely, a method of changing the illumination of his room. The other essential, a method of measurement by means of which an illumination could be identified with a previous illumination chosen as standard, might have been derived from his results. For example, it would seem to have been a simple matter for him to have chosen as standard the particular illumination at which the red stimulus of 2.5 mm. diameter, the blue and green of 12 mm. each, the yellow of 4.5 mm., and the white of 2 mm. were just recognizable at a distance of 5 m. Stimuli of these sizes, it will be seen from the tables, were just recognizable at this distance at the illumination called 12/15, when 15/15 represents the illumination "*bei günstige Tagesbeleuchtung.*" Using this condition as an index of the standard illumination, he could at any time have adjusted the illumination of the room by adding to or subtracting from the layers of tissue-paper covering the window, until the stimuli of these sizes were again just recognizable at the given distance. The accuracy and sensitivity of this method could have been tested by comparing the results of a series of determinations. An accurate and highly sensitive method sustaining some similarity in principle to the method suggested here is described in another paper in this volume of the REVIEW.¹

III. EXPERIMENTAL

The effect of change of illumination was forced upon our attention early in the investigation of the factors that influence the color sensitivity of the retina. For example, in preliminary work done by the writer on a well-lighted porch on Long Island, changes in color-tone were observed, when certain colors were compared in the central and in the peripheral retina, that are not found at all under the more intensive illumination of our optics-room when neither of the curtains is

¹ See footnote 2, p. 1.

drawn; and the peripheral limits of color were narrower by 5° to 12° . Furthermore, on a dark day, it was found that the limits of stimuli exposed through an opening in a white screen were reduced by about 4° as compared with the limits taken on a bright day. The change was less considerable with black and gray screens. The change in color-tone was most conspicuous in case of green.¹ On dark days, the green stimulus appeared as a pale unsaturated blue before becoming colorless in passing from the center to the periphery of the retina. This zone of blue was from 7° to 23° wide, in different meridians of the retina, with both white and black screens, but was wider with the black than with the white screen. On a sunny day, on the other hand, with the white screen green passed into bluish-green, then directly into gray, except in case of the upper regions where it appeared blue throughout a zone of about 4° in width. With the black screen, the blue zone was found only in the upper and temporal regions of the retina. The transition of green to yellow in the periphery that is generally reported in the literature was found in these experiments only when the gray screen was used. Yellow showed a color change that varied in amount with the degree of the general illumination. On a bright day with the white screen, it appeared reddish-orange. On a cloudy day, it was seen in the extreme periphery as a dark saturated red.

Working in our optics-room we found also that results taken on one day could not at all be duplicated on the following day. When the work was carried on under the most favorable conditions without special means of controlling illumination, namely, on bright days only, differences of 5° or more were found when the white screen was used. This necessitated a long series of observations if legitimate averages were to be obtained. Such a procedure is at best a poor makeshift and is besides of great disadvantage in many problems that come up in the work on color sensitivity. Particular instances of this may be found in investigations in which it is required to work in the region lying just within the limits of sensitivity, and in work on the after-images of stimuli in which no color is sensed.

¹ The green of the Hering series was used.

In the latter case the experiment requires that the stimulus be exposed just outside the limits of sensitivity determined with a given brightness condition, and that the observer should not be aware of the nature of the stimulus. In order to fulfill these requirements the experimenter must know the limits obtaining with a given brightness condition. It would be impossible to know this when the brightness conditions were subjected to the influence of changing illumination unless re-determinations were made at the beginning of each sitting and even frequently during its course. This would consume a great deal of time and would, besides, only roughly fulfill the requirements of the problem. A further and still more important example of the disadvantage may be found in the task we had set ourselves, namely, to investigate from point to point the sensitivity of the retina to each of the principal colors for three backgrounds in at least sixteen different meridians. In this work it is obvious that unless a standard illumination were provided, all comparative work would have to be done at one sitting. This is impossible. When time is taken between observations to guard against fatigue, at least three hours is required merely to outline the limits of sensitivity for a given color with one background for only one half of the retina. Even for this length of time there is no guarantee that the illumination has not altered. Thus at the outset of any extended investigation of color sensitivity, it is evident that, without a standard illumination, results will be of little comparative value.

In order better to know our factor and the ways in which it operates, a systematic investigation of the influence of changes of general illumination was carried on in our optics-room which is especially constructed to secure fine changes in illumination.¹ The experimentation was conducted by means of a rotary campimeter, described in full by Ferree, in the July number of the *American Journal of Psychology*.² Three observers acted as subjects. Since the results of all three are

¹ A description of this optics-room was given in the *PSYCHOLOGICAL REVIEW*, September number, 1912, pp. 367-368.

² Ferree, C. E., 'Description of a Rotary Campimeter,' *Amer. Journ. of Psychol.*, 1912, XXIII., pp. 449-453.

similar in their general bearing on the problem, space will be taken for the results of two of them only, *A* and *C*.

Rough preliminary experiments showed that the primary effect of decreasing the illumination was an increase in the amount of contrast induced across the stimulus by the campimeter screen. With the white screen, the increased induction was the most pronounced and was sufficient to cause large changes in the limits and in the color-tone of the stimulus. In order to investigate this effect in detail, gradual changes of illumination covering a wide range were made by means of the curtains with which our optics-room is furnished. Attention was given to the following points. (1) A quantitative estimate was made of the influence of change of illumination upon the brightness induction of the campimeter screen. (2) The effect of this induction upon the limits of color sensitivity was determined. (3) The limens of the colors were measured at different degrees of excentricity at different illuminations. And (4) the influence of change of illumination upon the effect of the preëxposure on the limens and limits of color was investigated. The degrees of illumination chosen for comparison were the standard illumination, the method of obtaining which was described in an earlier paper,¹ and a decreased illumination which was similar to that obtaining on a cloudy afternoon. Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles, the decreased 1.65 foot-candles.

I. QUANTITATIVE ESTIMATE OF THE INFLUENCE OF CHANGE OF ILLUMINATION UPON THE INDUCTION OF BRIGHTNESS BY THE SURROUNDING FIELD

The purpose of this investigation was to find out (1) how much the induction from white and black screens² is affected by a change in the general illumination; and (2) how much induction is gotten at decreased illumination from the gray screen which matches the color at standard illumination. The

¹ Ferree and Rand, *op. cit.*

² White and black screens are chosen because they represent the extreme cases of the effect of change of illumination.

induction in this latter case is caused by the change in the brightness relation between color and screens with decrease of illumination.¹ The campimeter screens served as inducing surface, grays of the brightness of the four principal colors of the Hering series both at standard and decreased illumination were used in turn as stimuli, and the amount of induction was estimated upon a measuring-disc, made up of adjustable sectors of the gray of the stimulus and white or black, according to the screen used. The measuring-disc was mounted on a motor which could be moved along the graded arm of the campimeter to any position from 20° to 92° . The gray stimulus was exposed through the opening of the screen in the usual manner. Two preliminary precautions were observed. (a) Since the brightness of the gray stimulus plus the induction of the screen was to be estimated by means of the measuring-disc, and since the brightness-value of the stimulus and of the disc changes with the amount of light that falls upon them, it was necessary to make sure before each measurement that the same amount of light fell upon each. This precaution was all the more necessary because the stimulus had to be placed behind the screen and the measuring-disc in front. In a given position of the apparatus, one or the other was apt to be shaded. The determination was made as follows: Measuring-disc, campimeter screen, and gray stimulus were all given the same brightness-value according to determinations made under conditions about which no doubt of the equality of the illumination of each could be entertained. Each was then placed in position for the experiment, and the position of the campimeter as a whole and of its various parts was adjusted until stimulus, screen, and measuring-disc were exactly matched in brightness-value. When an exact match was obtained we were guaranteed

¹ This latter determination is made to show that it is impossible to standardize the brightness of the surrounding field against the sudden and progressive changes of daylight that occur during the course of a single series of observations. These changes alter the brightness relation between the colored stimulus and the gray used as screen; therefore a match made at the beginning of a series will not hold throughout its course. For the same reason and to an equal degree the brightness relation between preexposure and colored stimulus changes with change of illumination. It is, therefore, equally impossible to standardize the brightness of the preexposure without some means of securing a standard illumination.

that all three were again equally illuminated. (b) The question arose whether brightness induction comes to its maximal value at once in the peripheral retina. A determination of the intensity curve of the contrast sensation was accordingly made at various points in the peripheral retina. It showed that contrast increases strongly for the first few seconds of stimulation. For this reason it was found to be necessary to make the judgment concerning the amount of induction of the screen, just as long after the induction had commenced as was done in the experiments to determine color sensitivity. In the color experiments an interval has to be allowed before the stimulus is exposed during which the observer obtains a steady fixation. During this interval of preexposure, the eye is being stimulated by the campimeter screen and by the card which covers the stimulus. To prevent the preexposure card from giving a brightness after-image which would fuse with and modify the stimulus, it should be chosen of a gray of the brightness of the color. In the same way, an interval has to be given in which to secure steady fixation when the amount of brightness induction is being measured. In order, then, to have the judgments made in each case the same length of time after induction had begun, it was necessary only to make the intervals of preexposure of equal duration and to require that the judgments of each kind be made directly at the end of the preexposure. In the case of the color experiments, the signal for the making of the judgment is the withdrawal of the preexposure card and the exposure of the stimulus. For the judgments of induction, however, in which case the stimulus was the gray of the brightness of the color, it is obvious that no preexposure card was needed, for preexposure and stimulus were required by the conditions of the experiment to be the same. In this case, a word-signal had to be given to indicate the termination of the preexposure interval and the instant at which the judgment was to be made.

Results when White and Black Screens were Used.—Observing these precautions as to the equality of the illumination of stimulus, screen, and measuring-disc, and as to the length of time the induction had had in which to increase before the

judgment was made, measurements were taken of the induction by white and black screens across grays of the brightness of the four principal colors at the illumination used. These measurements were made at various points of excentricity on the retina and for both standard and decreased illumination. The determination of the equality point between the stimulus and the measuring-disc was made as follows: The size of the white or black sector of the latter was changed until a preliminary judgment of equality was made. Then the j. n. d. on either side of this point was determined both by ascending and by descending series and an average of the results was taken as the final value of the induction. Measurements were taken at 25° and 40° on the temporal meridian, and at 55° and 70° on the nasal. The conditions at the nasal 55° point were very similar to those at 25° on the temporal side. The measurements at 70° nasal were midway in value between those at 25° and 40° on the temporal. The 40° point is very near the limits of color sensitivity in this meridian, and the induction here is very great. For one observer, the darker stimuli appeared black at this point, when the white background was used. In such cases, the difference between the induction at standard and at decreased illumination is more clearly shown by the observations made at 25° temporal meridian and at 55° and 70° nasal meridian than at 40° temporal. We have, however, chosen for two reasons to present in the following table only the results obtained in the temporal meridian. (1) The results obtained in this meridian demonstrate sufficiently well all the facts that need be taken into consideration. Space will not, therefore, be given to the results for both meridians. (2) The second point of our problem requires us to correlate the increased amount of induction caused by a given decrease of illumination with the change in the color limits it produces. The limits of color sensitivity can be more easily investigated in the temporal meridian because the sensitivity to some colors extends in the nasal region beyond the 92° point, which is the limit of measurement for the apparatus we used. This is true in particular in case of observer *C* as may be seen in Table XI. Both purposes of the investigation are, then,

better satisfied by results obtained in the temporal meridian.

The results show in general the following facts.

1. The amount of induction from the white screen is greater than that from the black screen.

2. The amount of induction increases with the distance from the fovea.

3. The amount of induction increases with decrease of illumination.¹

4. The amount of increase under decreased illumination is greater in case of the white screen than in case of the black screen.

5. The white and black screens induce more contrast across the stimuli that are farthest removed from them in brightness, and least across those which are most like them. That is, the white screen induces more black across the gray of the brightness of blue than across a gray of the brightness of yellow; and the black screen induces more white across the gray of the brightness of yellow than across a gray of the brightness of blue.

Results are given in detail in Tables I. and II. Table I. gives the results for observer *A* taken on the temporal meridian, and Table II., the results for observer *C* for the same meridian. There is some difference in the amount of induction reported by the different observers, but since the preceding general statement of results is clearly borne out in every case, it is not deemed necessary to give space to results from all the observers used. In these tables, column 1 gives the degree of eccentricity at which the observation was made; columns 2, 3, and 4 show respectively the stimulus used, and the amounts of induction from the white and the black screens at standard illumination. Columns 5, 6, and 7 give the same data for decreased illumination.

Results when the Gray Screen Matching the Colored Stimulus in Brightness at Standard Illumination is Used.—It was neces-

¹ This statement is meant to apply only to the range of illumination worked with. The induction was not measured when the illumination was very low, nor when it was very intensive.

TABLE I

A. SHOWING THE AMOUNT OF CONTRAST INDUCED BY THE WHITE AND THE BLACK SCREENS AT STANDARD AND DECREASED ILLUMINATION UPON THE GRAYS OF THE BRIGHTNESSES OF THE COLORED STIMULI AT STANDARD AND DECREASED ILLUMINATION¹

Fixation	Standard Illumination			Decreased Illumination		
	Stimulus (Gray of Brightness of Each of the Four Colors at Standard Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen	Stimulus (Gray of Brightness of Each of the Four Colors at Decreased Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen
25°	gray No. 2	Black 135°	White 110°	gray No. 2	Black 220°	White 170°
	gray No. 8	Black 155°	White 60°	gray No. 6	Black 270°	White 80°
	gray No. 24	Black 230°	White 28°	gray No. 41	Black 323°	White 40°
	gray No. 32	Black 290°	White 12°	gray No. 20	Black 330°	White 30°
40°	gray No. 2	Black 200°	White 300°	gray No. 3	Black 320°	White 360°
	gray No. 8	Black 300°	White 132°	gray No. 5	Black 360°	White 180°
	gray No. 24	Black 0°	White 60°	gray No. 50	Black 360° ²	White 0° ³
	gray No. 29	Black 360°	White 28°	gray No. 13	Black 360°	White 100°

¹ It is obvious that the method of expressing the amount of brightness induction used in this and the following tables gives an underestimation. Suppose, as is shown in Table I., that No. 24 Hering gray has been darkened by induction until it matches in brightness a disc made up of 230° of black and 130° of the No. 24 gray. The amount of induction is greater than is represented by the 230° of black because the induction has not lessened the amount of light coming to the eye from the gray paper while the addition of 230° of black to the measuring disc has cut off approximately 2/3 of the light coming from the gray paper. That is, in the one case enough black has been added by induction to reduce 360° of No. 24 gray to the given point in the brightness scale, while in the other enough black was added by direct mixing to lower only 130° of No. 24 gray to this point in the scale. Moreover, the underestimation will be increased by this method of measuring in proportion as the amount of induction is increased because the greater the induction is the more black and the less gray will have to be used in the measuring-disc. All that can be said accurately is that a certain gray darkened or lightened by induction matches in brightness a gray made up of a certain amount of the given gray plus a certain amount of black or white. The exact amount of the induction can not be separated out. Further, just because the brightness added by contrast does not alter the amount of light coming to the eye while the brightness added in any method of measurement does change this amount of light, the writer knows of no way by which an exact expression can be attained. The

TABLE II

OBSERVER C

Fixation	Standard Illumination			Decreased Illumination		
	Stimulus (Gray of Brightness of Each of the Four Colors at Standard Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen	Stimulus (Gray of Brightness of Each of the Four Colors at Decreased Illumination)	Amt. Induction of White Screen	Amt. Induction of Black Screen
25°	gray No. 2	Black 70°	White 55°	gray No. 2	Black 130°	White 70°
	gray No. 8	Black 84°	White 48°	gray No. 6	Black 155°	White 59°
	gray No. 24	Black 93°	White 30°	gray No. 40	Black 187°	White 45°
	gray No. 32	Black 160°	White 15°	gray No. 17	Black 244°	White 22°
40°	gray No. 2	Black 110°	White 200°	gray No. 3	Black 216°	White 340°
	gray No. 7	Black 142°	White 160°	gray No. 4	Black 230°	White 320°
	gray No. 24	Black 180°	White 95°	gray No. 50	Black 360° ⁴	White 0° ₆
	gray No. 27	Black 214°	White 35°	gray No. 7	Black 300°	White 108°

method she has used, however, does serve as a means of comparing the amounts of induction occurring under different conditions sufficiently accurately for her purpose at this point.

²The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match thus could not be attained with black 360° as the table indicates.

³There was no brightness induction in this case because the stimulus, gray No. 50, matches in brightness the black paper which formed the campimeter screen.

⁴See footnote 2 above.

⁵See footnote 3 above.

sary to perform the experiments bearing on this point at decreased illumination only. For them the campimeter screens which matched in brightness the four principal colors of the Hering series at standard illumination served as inducing surfaces. For the contrast surfaces, grays of the brightness of these colors at decreased illumination were chosen. The methods of measuring, precautions in working, parts of the retina investigated, etc., were the same as in the preceding determinations. The following general statement of results may be made. (1) At the 25° point the brightness of yellow was found not to have changed at all with the decrease of illumination produced by changing the illumination from the value selected as standard to the value selected for the comparison; the brightness of green lightened by an amount equal to the difference between No. 8 and No. 6 of the Hering series of grays; red darkened by an amount equal to the difference between No. 24 and No. 40; and blue lightened by an amount equal to the difference between No. 32 and No. 20. The amount of induction by the gray screen of the original brightness of the color upon the gray stimulus of the brightness of the color as altered by the decreased illumination, expressed in terms of Hering white and black, was for yellow 0° , for green 60° of white, for red 27° of black, and for blue 20° of white. (2) At the 40° point, the yellow darkened by an amount equal to the difference between No. 2 and No. 3 of the Hering grays; green lightened by an amount equal to the difference between No. 8 and No. 5; red darkened by an amount equal to the difference between No. 28 and No. 50; and blue lightened by an amount equal to the difference between No. 28 and No. 13. The amount of induction produced by these changes was for yellow 280° of black, for green 130° of white, for red 360° of black, and for blue 60° of white. These results are shown in detail in Table III.

2. THE EFFECT OF THESE AMOUNTS OF INDUCTION UPON THE LIMITS OF COLOR SENSITIVITY

In order to obtain an estimate of the range of effect upon the limits of color sensitivity of the induction of the screens

TABLE III

A. SHOWING THE AMOUNT OF CONTRAST INDUCED AT DECREASED ILLUMINATION ON GRAYS OF THE BRIGHTNESS OF THE COLORS AT DECREASED ILLUMINATION BY THE GRAY SCREENS MATCHING THE COLORS IN BRIGHTNESS AT STANDARD ILLUMINATION

Fixation	Stimulus	Screen	Amount of Induction
25°	gray No. 2	gray No. 2	0°
	gray No. 6	gray No. 8	white 60°
	gray No. 41	gray No. 24	black 27°
	gray No. 20	gray No. 32	white 20°
40°	gray No. 3	gray No. 2	black 280°
	gray No. 5	gray No. 8	white 130°
	gray No. 50	gray No. 24	black 360° ¹
	gray No. 13	gray No. 28	white 60°

at standard and at decreased illumination, the breadth of the color zones was determined at both illuminations (1) when white and black served in turn as campimeter screens; and (2) when a gray matching the color in brightness at standard illumination was used. The preëxposure was in each case to a gray of the same brightness as the stimulus at the illumination used. The point at which the color lost all trace of its original quality was recorded as the limit of sensitivity.

Results when White and Black Screens Were Used.—When the stimulus color is gotten by reflection from a pigment surface, two factors operate to give a change of result when the illumination is decreased. (1) There is a decrease in the amount of colored light coming to the eye. (2) There is an increase in the inductive action of the screen due to the change in the brightness relation of stimulus to screen and to the increased sensitivity of the eye to brightness contrast at decreased illumination.

In order to find out how much of our results with the white and black screens should be attributed to the decrease in the amount of colored light coming to the eye produced by the decreased illumination, and how much to the increased inductive action of the screens, the limits of sensitivity were also determined at both illuminations with the screens of the gray into

¹ The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match thus could not be attained with black 360° as the table indicates.

which the color disappears in the peripheral retina. From the values obtained with the three screens at both illuminations, the amount of change due to decrease in the amount of colored light coming to the eye and the amount due to induction by the white and black screens were calculated as follows. (a) From the number of degrees expressing the limits for a given color at standard illumination with a screen of the brightness of the color at that illumination was subtracted the number expressing its limit at decreased illumination with a screen of the brightness of the color at the decreased illumination. That this gave the number of degrees the zone of sensitivity was narrowed by the decrease in the energy of the stimulus may be said with the following qualification. If there is any influence upon color sensitivity of the local brightness-adaptation of the retina produced by the change in the general illumination, it is, of course, included in this effect. But, since this influence would have to be brought about by previous exposure to the illumination in question, it can be reduced to a minimum by guarding against an exposure to it for any considerable length of time. The effect of whatever adaptation there may be, however, can not be isolated or separated out from the above result, and the value expressing the amount the limit is narrowed by the actual decrease of the energy of colored light coming to the eye cannot, strictly speaking, be obtained. But it is probable that the adaptation effect is not sufficiently strong to influence the limits, since the sensitivity of the extreme peripheral retina falls off very abruptly from point to point. The difference, then, between the color limit obtained at standard illumination and the limit at decreased illumination, when in both cases there is no brightness induction from the screen, may be said to approximate the effect upon the limits produced by the decrease in the amount of colored light coming to the eye. (b) Figures can be obtained, however, from our results, which express the amount by which the zones are narrowed by the change in the inductive action of the white and black screens produced by decreasing the illumination, that are not open to theoretical questioning; for the influence of local brightness-adaptation, if there be any, is a constant for all screens at the same illu-

mination. If then, the number of degrees which expresses the limits of sensitivity for either the white or the black screen at decreased illumination is subtracted from the number expressing the limit with a screen of the gray of the brightness of the color at this illumination, the result will represent the extent to which the limit was narrowed by the action of induction alone. The results show in general the following facts:

1. At standard illumination, induction from the white screen narrows the limits of yellow and red; induction from the black screen narrows the limits of blue and green. The difference is in no case more than 4° .

2. At decreased illumination, the induction from the white screen narrows the limits of all the colors much more considerably than does the induction from the black screen.¹

3. The values expressing the narrowing of the limits caused by decrease of illumination without induction are greatest in case of those colors which undergo maximum change of brightness in passing into the periphery, namely, for blue and red.

We have shown by the results of the preceding section, that the increased induction produced by decrease of the general illumination is greater for the white screen than for the black, and, by the results of this section, that this increase is effective to the extent of narrowing the limits of sensitivity to all colors from 5° to 12° with this screen. With the black screen, the limits were narrowed from 3° to 6° . At standard illumination, the limits were narrowed only from 1° to 4° with either the white or the black screens.

Results in detail are given in Tables IV. and V., taken from the temporal meridians of the observers whose observations are recorded in Tables I. and II. In column 1, Tables IV. and V., is given the stimulus. Column 2 shows the limit of sensitivity to the stimulus at standard illumination with a screen of a

¹ For observer *A* the results for green present an exception. At the decreased illumination used the green stimulus appeared bluish in the central retina. The induction of the black screen caused it to appear as a pale blue at a comparatively slight degree of excentricity. According to our definition of color limit, this point is the limit of green. It is, however, obvious that the exception is due rather to the qualitative than to the quantitative effect of brightness upon color.

gray of the brightness of the color at standard illumination; column 3 shows the limit with a white screen; and column 4 with a black screen. Column 5 shows the limit at decreased illumination with a screen of the brightness of the color at decreased illumination; column 6 shows the limit with a white screen; and column 7 with a black screen.

TABLE IV

A. SHOWING THE COLOR LIMITS AT STANDARD AND DECREASED ILLUMINATION (a) WITH GRAY SCREENS OF THE BRIGHTNESSES OF THE COLORS AT THE ILLUMINATION USED; AND (b) WITH WHITE AND BLACK SCREENS

Stimulus	Standard Illumination			Decreased Illumination		
	Limit with Gray Screen of Brightness of Color at Standard Illumination	Limit with White Screen	Limit with Black Screen	Limit with Gray Screen of Brightness of Color at Decreased Illumination	Limit with White Screen	Limit with Black Screen
Yellow.....	44°	42°	45°	43°	35°	43°
Green.....	37°	37°	34°	36°	31°	27°
Red.....	43°	42°	44°	40°	31°	40°
Blue.....	50°	50°	49°	48°	36°	43°

TABLE V

OBSERVER C

Stimulus	Standard Illumination			Decreased Illumination		
	Limit with Gray Screen of Brightness of Color at Standard Illumination	Limit with White Screen	Limit with Black Screen	Limit with Gray Screen of Brightness of Color at Decreased Illumination	Limit with White Screen	Limit with Black Screen
Yellow.....	49°	46°	50°	46°	36°	44°
Green.....	44°	42°	40°	41°	28°	33°
Red.....	45°	41°	45°	41°	34°	41°
Blue.....	56°	55°	53°	50°	38°	44°

Tables VI. and VII. have been compiled from Tables IV. and V. to show the following facts.

(1) How much the decrease of illumination narrowed the limits of color sensitivity by causing a decrease in the energy of the light waves coming to the eye. This was determined by subtracting the value of the limit at decreased illumination with the screen of a gray of the brightness of the color at decreased illumination from its value at full illumination with the gray screen of the brightness of the color at full illumination.

(2) How much the limits were narrowed by the action of the white and black screens at decreased illumination. This was ascertained by subtracting the values of the limit with the white and the black screen at decreased illumination from the value of the limit at decreased illumination with the gray screen of the brightness of the color at this illumination. (3) How much more the limits were narrowed by the white and the black screens at decreased than at full illumination. This was computed for the white screen, for example, as follows. The quantity, limit at decreased illumination for gray screen of brightness of color at decreased illumination, minus limit for white screen at decreased illumination, is subtracted from the

TABLE VI

A. SHOWING (1) HOW MUCH THE LIMITS WERE NARROWED BY DECREASE IN THE AMOUNT OF COLORED LIGHT COMING TO THE EYE; (2) HOW MUCH THEY WERE NARROWED BY INCREASED INDUCTION OF WHITE AND BLACK SCREENS AT DECREASED ILLUMINATION; AND (3) HOW MUCH MORE THEY WERE NARROWED BY INDUCTION OF WHITE AND BLACK SCREENS AT DECREASED THAN AT FULL ILLUMINATION

Stimulus	How Much Limits were Narrowed by Decrease in Amount of Colored Light Coming to the Eye	How Much Limits were Narrowed by Induction of White Screen	How Much Limits were Narrowed by Induction of Black Screen	How Much More Limits were Narrowed by White Screen at Decreased than at Full Illumination	How Much More Limits were Narrowed by Black Screen at Decreased than at Full Illumination
Yellow.....	1°	8°	0°	6°	3°
Green.....	1°	5°	9°	5°	6°
Red.....	3°	9°	0°	8°	3°
Blue.....	2°	12°	5°	12°	4°

TABLE VII

OBSERVER C

Stimulus	How Much Limits were Narrowed by Decrease in Amount of Colored Light Coming to the Eye	How Much Limits were Narrowed by Induction of White Screen	How Much Limits were Narrowed by Induction of Black Screen	How Much More Limits were Narrowed by White Screen at Decreased than at Full Illumination	How Much More Limits were Narrowed by Black Screen at Decreased than at Full Illumination
Yellow.....	3°	10°	2°	7°	3°
Green.....	3°	13°	8°	11°	4°
Red.....	4°	7°	0°	3°	0°
Blue.....	6°	12°	7°	11°	3°

quantity, limit at full illumination for gray screen of brightness of color at full illumination minus limit for white screen at full illumination. A similar computation was made for the black screen.

Results when a Gray Screen Matching the Color in Brightness at Standard Illumination is Used.—In these experiments a determination was made of the amount the limits of sensitivity are changed by the brightness induction caused by the alteration of the brightness relation between stimulus and screen with decrease of illumination, when a screen is used which matches the color in brightness at standard illumination. This determination was made as follows. An estimate was made of the amount the limits were narrowed by decrease of illumination when a screen of the brightness of the color at standard illumination is used for both standard and decreased illuminations. From this result was subtracted the amount the limits were narrowed by decrease of illumination when the screen is made in turn of the brightness of the color at standard and decreased illumination. The difference obtained represents the value sought. It is given in Table VIII.

TABLE VIII

A. SHOWING HOW MUCH THE COLOR LIMITS WERE NARROWED AT DECREASED ILLUMINATION BY THE INDUCTION OF THE SCREEN WHICH MATCHED THE COLOR IN BRIGHTNESS AT STANDARD ILLUMINATION

Stimulus	Screen of Brightness of Color at Decreased Illumination	Limit	Screen of Brightness of Color at Standard Illumination	Limit	Amount Limit was Narrowed by Change in Brightness Relation Between Stimulus and Screen Caused by Decreased Illumination
Yellow...	gray No. 3	43°	gray No. 2	41°	2°
Green ...	gray No. 5	36°	gray No. 8	29°	7°
Red	gray No. 50	40°	gray No. 24	33°	7°
Blue.....	gray No. 13	48°	gray No. 28	46°	2°

3. THE EFFECT OF THESE AMOUNTS OF INDUCTION UPON THE LIMEN OF COLOR AT DIFFERENT DEGREES OF EXCENTRICITY

We have shown the effect of decreasing the general illumination upon the color sensitivity of the peripheral retina with

gray, white, and black screens, by the effect on the limits of sensitivity. This is only an indirect means of estimating its influence, for the results obtained cannot be translated into terms of direct measurement, owing to the irregular decrease in sensitivity of the peripheral retina from the fovea outwards. In this section, we shall measure the influence of changes of illumination directly by the changes produced in the limen of sensation at various angles of excentricity. As in the previous section, measurement will be made of the effect upon sensitivity (1) of the decrease in the amount of colored light coming to the eye, produced by the decrease of illumination, (2) of the difference in the inducing power of the white and black screens, and (3) of the change in the brightness relation of stimulus to background.

To determine the first of these three points, a campimeter screen had to be selected that gave no brightness contrast with the stimulus. To provide for differences in the brightness of the colors at the different points observed for the two illuminations at which we worked, a preliminary determination of the brightness of the sensation at these points was made at both illuminations by the flicker method. The brightness of the screen was chosen in each case of the brightness of the color according to these determinations. To eliminate the effect of preëxposure, the stimulus previous to exposure was in every case covered by a gray of the brightness of the color for the illumination used at the point of the retina at which we were working. Thus no brightness after-image was carried over to exert an inhibitive action upon the color sensation. The stimulus was a disc compounded of sectors of the color and of the gray of the brightness of the color for the illumination used at the point of the retina under investigation. The proportions of the sectors were altered until the observer gave the judgment of just noticeable color. The average of judgments made in ascending and descending series was chosen as the final value of the limen. The difference between the limens at standard and decreased illumination was taken as the measure of the loss in intensity which the stimulus had sustained by the decrease of illumination.

The effect upon the color limen of the increased induction from the white and black screens was shown by the same method, with the exception that the white and black screens were substituted for the gray of the brightness of the color. The stimulus was a disc composed of sectors of color and gray of the brightness of the color at the angle of excentricity at which the determination was made.

The effect of the change in the brightness relation between the stimulus color and the screen produced by decrease of illumination was shown as follows. An estimate was made of the amount the limens are raised by the decrease of illumination when a screen was used for both standard and decreased illumination that had a brightness value equal to the color at standard illumination. From these results was subtracted the amount the limens were raised by decreasing the illumination when the screens were made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. These results are of particular importance because they show that the influence of the brightness of the surrounding field can not be eliminated even when a screen of the brightness of the color is used unless some means be had of maintaining the general illumination of the room constant.

Table IX. shows how much the limens of sensitivity were raised at the fovea and at points 15° , 25° and 30° from the fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye produced by the decrease in the general illumination. The results of this table may be generalized as follows:

1. The limen of color is higher in the periphery than in the center of the retina at both illuminations.
2. The limen of color is higher at decreased illumination than at standard illumination.
3. The direct effect upon the intensity of the sensation produced by decreasing the illumination is shown by the limen determinations to be inconsiderable. In the central retina, the difference is but 2° or 3° . In the peripheral retina at the points considered there is a difference of from 10° to 20° .

TABLE IX

A. SHOWING HOW MUCH THE LIMENS OF SENSITIVITY WERE RAISED AT THE FOVEA, AND AT POINTS 15°, 25°, 30° FROM THE FOVEA IN THE HORIZONTAL MERIDIAN ON THE TEMPORAL SIDE BY THE DECREASE IN THE AMOUNT OF COLORED LIGHT COMING TO THE EYE PRODUCED BY THE DECREASE IN THE GENERAL ILLUMINATION

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	Limen at Standard Illumination with Screen of Brightness of Color at Standard Illumination	Limen at Decreased Illumination with Screen of Brightness of Color at Decreased Illumination	How Much Limen was Raised at Decreased Illumination
Yellow.....	0°	18°	20°	2°
	15°	22°	32°	10°
	25°	35°	40°	5°
	30°	50°	65°	15°
Green.....	0°	20°	20°	0°
	15°	27°	28°	1°
	25°	40°	50°	10°
Red.....	0°	9°	11°	2°
	15°	9°	13°	4°
	25°	17°	25°	8°
	30°	25°	45°	20°
Blue.....	0°	9°	10°	1°
	15°	10°	13°	3°
	25°	12°	15°	3°
	30°	20°	40°	20°

TABLE X

A. SHOWING THE COLOR LIMENS AT STANDARD AND DECREASED ILLUMINATIONS WITH WHITE AND WITH BLACK SCREENS

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	White Screen		Black Screen	
		Limen at Standard Illumination	Limen at Decreased Illumination	Limen at Standard Illumination	Limen at Decreased Illumination
Yellow ...	0°	22°	25°	28°	30°
	15°	25°	50°	35°	45°
	25°	50°	80°	42°	60°
	30°	80°	125°	60°	90°
Green....	0°	22°	25°	28°	30°
	15°	26°	36°	35°	43°
	25°	30°	75°	75°	220°
Red.....	0°	13°	20°	10°	14°
	15°	19°	35°	13°	19°
	25°	30°	55°	23°	35°
	30°	50°	330°	29°	58°
Blue.....	0°	17°	22°	10°	12°
	15°	25°	40°	12°	17°
	25°	35°	60°	18°	25°
	30°	40°	90°	30°	60°

Table X. shows the color limens at both standard and decreased illuminations when white and black screens are used, at the fovea and at points 15° , 25° , and 30° in the horizontal meridian on the temporal side.

Table XI. has been compiled from Tables IX. and X. to show how much greater the limens were for white and black screens at decreased than at full illumination; how much of the effect may be ascribed to the reduction of the amount of colored light coming to the eye; and how much to the increased induction of the screens. It will be seen from the results of this table that the loss of the sensation in intensity due to the increased brightness induction is much greater than that caused by the reduction in the amount of colored light coming to the eye.

TABLE XI

A. SHOWING HOW MUCH GREATER THE LIMENS WERE WITH WHITE AND BLACK SCREENS AT DECREASED THAN AT STANDARD ILLUMINATION AND HOW MUCH OF THIS EFFECT MAY BE ASCRIBED TO THE REDUCTION IN THE AMOUNT OF COLORED LIGHT COMING TO THE EYE AND HOW MUCH TO THE INCREASED INDUCTIVE ACTION OF THE SCREENS

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	White Screen			Black Screen		
		Total Amount Greater	Amount Due to Decrease in Amount of Colored Light Coming to Eye	Amount Due to Increased Induction of Screen	Total Amount Greater	Amount Due to Decrease in Amount of Colored Light Coming to Eye	Amount Due to Increased Induction of Screen
Yellow...	0°	7°	2°	5°	12°	2°	10°
	15°	28°	10°	18°	23°	10°	13°
	25°	45°	5°	40°	25°	5°	20°
	30°	75°	15°	60°	35°	15°	25°
Green...	0°	5°	0°	5°	10°	0°	10°
	15°	8°	1°	7°	16°	1°	15°
	25°	35°	10°	25°	180°	10°	170°
Red....	0°	11°	2°	9°	5°	2°	3°
	15°	26°	4°	22°	10°	4°	6°
	25°	38°	8°	30°	18°	8°	10°
	30°	305°	20°	285°	33°	20°	13°
Blue....	0°	13°	1°	12°	3°	1°	2°
	15°	30°	3°	27°	7°	3°	4°
	25°	48°	3°	45°	13°	3°	10°
	30°	70°	20°	50°	40°	20°	20°

It was shown in Table III. that quite a great deal of brightness induction is caused by the change in brightness relation between color and screen produced by decreasing the illumination. Table VIII. shows how much this induction narrows the limits of sensitivity to the four colors used. Table XII. shows how much the limens are raised when the illumination is decreased by the inductive action caused by the change in the brightness relation between stimulus color and gray screen of the brightness of the color at standard illumination.

TABLE XII

A. SHOWING HOW MUCH THE COLOR LIMENS WERE RAISED AT DECREASED ILLUMINATION BY THE INDUCTION OF THE SCREENS WHICH MATCHED THE COLOR AT STANDARD ILLUMINATION

Stimulus	Point on Horizontal Temporal Meridian at Which Limen was Taken	Limen with Screen of Brightness of Color at Decreased Illumination	Limen with Screen of Brightness of Color at Standard Illumination	Amount Limen was Raised by Change in Brightness Relation Between Stimulus and Screen Caused by Decrease of Illumination
Yellow.	0° 15° 25° 30°	20° 32° 40° 65°	20° 32° 40° 116°	0° 0° 0° 51°
Green.	0° 15° 25°	20° 28° 50°	20° 40° 190°	0° 12° 140°
Red.	0° 15° 25° 30°	11° 13° 25° 45°	11° 24° 48° 150°	0° 11° 23° 105°
Blue.	0° 15° 25° 30°	10° 13° 15° 40°	12° 16° 23° 55°	2° 3° 8° 15°

4. THE INFLUENCE OF CHANGE OF ILLUMINATION UPON THE ACTION OF THE PREEXPOSURE ON THE LIMENS AND LIMITS OF COLOR

The brightness of the preëxposure exerts an influence upon the color observation because the eye carries over an after-image from the preëxposure into the color observation. If, for example, the preëxposure is to black, a white after-image is

aroused which fuses with the succeeding color sensation and strongly reduces its saturation. The effect of preëxposure is especially strong in the peripheral retina because a very strong brightness after-image is aroused in the peripheral retina by a very short period of stimulation. It is very difficult for the writer to predict from the data she has at hand with regard to the effect of change of illumination upon the sensitivity of the peripheral retina to the brightness after-image just what will be the effect of change of illumination upon the action of preëxposure on the color sensitivity of the peripheral retina. But even though there be no change in the sensitivity of the peripheral retina to the brightness after-image with change of illumination, it is obvious that there will be some effect of the change of illumination because of the change in the brightness relation of the preëxposure card to the colored stimulus. In case the stimulus light is gotten by reflection from pigment surfaces, this change of brightness relation is due to the shift in the brightness of the colors produced by the change in the illumination. In case transmitted light is used as stimulus, the brightness of the stimulus color is independent of changes in illumination and will remain constant; but a change in the brightness relation of stimulus to preëxposure will occur because the preëxposure will lighten or darken with change of illumination. The writer hopes to make the quantitative investigation of this point the subject of a future study. At present she can only point out that if a guarantee is wanted that the effect of the brightness of the preëxposure is eliminated from the results of the observation, the preëxposure must be to a gray of the brightness of the color and the illumination of the room must be kept constant.

IV. CONCLUSION

The foregoing results show how strongly the changes in the illumination of the visual field influence the color sensitivity of the peripheral retina, particularly when the stimulus is surrounded by a white field. They also show that the influence of surrounding field can not be eliminated even by means of a campimeter screen of the brightness of the color unless some

means be had of keeping the general illumination of the room constant. It is obvious without further comment how important it is that a method be devised to standardize this factor. The preceding experiments indicate that without this standardization, no experiment can be repeated from time to time under the same conditions relative to any one of the brightness factors that influence color sensitivity. Results thus obtained are far from comparable. As was stated earlier in the paper a method of standardizing was described in an earlier paper in this volume of the *REVIEW*.¹

¹See footnote, 2, p. I.

It was the writer's intention to have had the present article precede the one in which the method of standardizing is described, but owing to limited space in the July number the Editor was compelled to use for that number the shorter article.

TESTS FOR THE EFFICIENCY OF THE EYE UNDER DIFFERENT SYSTEMS OF ILLUMINATION AND A PRELIMINARY STUDY OF THE CAUSES OF DISCOMFORT.*

BY C. E. FERREE.

Synopsis:—Besides outlining (I) the problem which confronts the investigator who would determine the effects of various lighting systems on the eye, this paper discusses: (II) the scale or general level of efficiency of the eye under different systems of lighting, with brief comments on the conventional tests for the efficiency of the eye such as, (*a*) color discrimination, (*b*) brightness discrimination, (*c*) visual acuity—the latter tests, modified, it is contended are adequate for the determination of the general level of efficiency of the unfatigued eye; (III) loss of visual efficiency as the result of a period of work—here it is contended that each of the aforementioned tests fails to show a true loss of visual efficiency, and a new test is described. The paper is concluded (IV) with a brief statement of some of the causes of ocular discomfort under various conditions, and a description of a method of making a comparative estimate of discomfort.

I. INTRODUCTION.

In 1911 the American Medical Association appointed a committee to study the effect of different lighting systems on the eye. The writer was asked to share in the work of this committee. The problem presented to him was to furnish tests that would show the effect of different lighting systems on the eye and more especially to devise, if possible, a test that would show a loss of efficiency as the result of three or four hours of work under an unfavorable lighting system. It is the purpose of the following paper to give a preliminary report of the work that has been carried on by the writer in this field during the past year.

Confronting the problem of the effect of lighting systems on the eye, it is obvious that the first step toward systematic work is to obtain some means of making a definite estimate of this effect. The prominent effects of bad systems of lighting are loss of efficiency, temporary and progressive, and eye discomfort. Having devised methods which after six months of testing he has found to be accurate and practicable, the writer has under-

* A paper read at the sixth annual convention of the Illuminating Engineering Society, Niagara Falls, Ont., September 16-19, 1912.

taken to determine (1) the lighting conditions that give in general the highest level or scale of visual efficiency, (2) the conditions that give the least loss of efficiency for continued work, and (3) the conditions that cause the least discomfort. This plan of work, it is scarcely needful to remark, will involve a wide range of experimentation. The crux of the problem, as the writer conceives it, is, however, to secure reliable methods of estimating effect. Having these methods, the factors whatever they may be, intensity, quality, position of light relative to the eye, etc., can be varied one at a time and the effects be determined. From these effects it should not be difficult to ascertain what lighting conditions are best for the eye and what is the relative importance of the factors that go to make up these conditions. Further it should be possible on the practical side to test out and perfect a lighting system, so far as its effect on the eye is concerned, before we put it on the market.*

In this report nothing more will be attempted than to indicate what methods may be used in the three steps of the problem as outlined above.

II. THE SCALE OR GENERAL LEVEL OF EFFICIENCY OF THE EYE UNDER DIFFERENT SYSTEMS OF LIGHTING.

A general survey of the field shows that at different times the following tests have been used in one capacity or another for determining the efficiency of the eye: brightness discrimination, color discrimination, and visual acuity. No extensive use, if any at all, has been made of any of these with the exception of visual acuity in connection with problems of the type here considered, but the fitness of their application in some form to such problems is evident at a glance. If the eye's efficiency is to change at different times and under different conditions of lighting, it should be manifested in changes in brightness discrimination, color discrimination, or visual acuity. The first step in our work would, then, seem to be to devise for these points tests which are sufficiently sensitive for use in work of the kind we have in hand. The general nature of these tests is too familiar to need detailed mention here. A few special points may, however, be given in passing. (1) The threshold or limen test is the most sensitive and practical

* This latter point was suggested to the writer by reading Dr. Ives' discussion of this paper (p. 57).

for color sensitivity. In making this test the pre-exposure¹ and the surrounding field² should be of a gray of the brightness of the color at or near its threshold value. Further, the illumination of the room must be kept constant from test to test.³ If the colored light is to be obtained by reflection, disks of standard

¹ By pre-exposure is meant what the eye rests on immediately preceding its stimulation by color. It is obvious that there must always be some pre-exposure and, unless care be taken to eliminate its effect, it will influence the eye's sensitivity to color. Even closing the eye, as is often done before stimulating by color, is the equivalent of giving a black pre-exposure. All color must of course be eliminated from the pre-exposure. It should also be of the same brightness as the color by which the eye is to be stimulated. If not it gives a brightness after-image which mixes with the succeeding color impression and reduces its saturation. This reduction of saturation takes place apparently at some physiological level posterior to the seat of the positive, negative, and contrast color processes commonly supposed to be located in the retina. (See Ferree and Rand: "The Fusion of Brightness with Color—The Locus of the Action," *Journal of Philosophy, Psychology and Scientific Methods*, VIII, 1911, p. 294.) If the pre-exposure is lighter than the color it adds by after-image a certain amount of black to the succeeding color impression and, if darker, it adds a certain amount of white. Since white inhibits color more than black, the effect of a dark pre-exposure is to reduce the sensitivity to color more than the effect of a light pre-exposure. But since both white and black as after-effect reduce the sensitivity to color, the eye is rendered more sensitive when no after-image is given, i. e. when the pre-exposure is of the same brightness as the color. The pre-exposure therefore should be to a gray of the brightness of the color. No brightness after-image will be added thereby to the succeeding color impression to modify either its saturation or color tone.

² When the surrounding field is either lighter or darker than the color, brightness is induced by contrast across the colored surface. When the surrounding field is lighter than the color, a certain amount of black is induced, and when darker, a certain amount of white is induced. As stated above, the mixture of this white or black with color, although it does not alter the amount of colored light coming to the eye, reduces the saturation of the color. The effect of brightness contrast can be eliminated only by making the brightness of the surrounding field a gray of the brightness of the color. This can be done by means of a gray screen around the color, or by a larger gray disk in case a color mixer is used.

³ In case the colored light used for the stimulus is obtained by reflection from a pigment surface, a change in the general illumination of the field of vision affects the results of the sensitivity tests in the following ways. (1) It changes the amount of colored light coming to the eye. (2) By changing its brightness adaptation it changes the sensitivity of that part of the retina upon which the colored light falls. (3) By changing the sensitivity of the eye to brightness after-image and contrast, it changes the amount of brightness added to the color as the result of pre-exposure and surrounding field, and therefore changes the effect of pre-exposure and surrounding field upon the color impression. Moreover, the effect of pre-exposure and surrounding field cannot be eliminated even when both are made of the brightness of the color for some given illumination, unless that illumination be kept constant throughout the test for, when it changes, the brightness of the color and of the grays used as pre-exposure and surrounding field does not change in equal amounts; hence, the brightness equality which is needed cannot be maintained. In case the colored light is not gotten by reflection from a pigment surface but is obtained from monochromatic sources from standard filters or from the spectrum, only the last two of the factors stated above influence the results of the tests for color sensitivity. In the tests made by the writer, the general illumination was rendered constant by methods to be described later in the paper.

Although for the purposes of this work the tests for color sensitivity could never be conducted in the dark-room, still it may be of general interest to note at this point that the elimination of the effect of pre-exposure and surrounding field cannot be accomplished in work on color sensitivity done in the dark-room, because in the dark-room the pre-exposure and surrounding field cannot be made of the brightness of the color. They will always therefore exert an effect on the color impression. Moreover since the colors all differ in brightness, this effect will be exerted in different amounts on the different colors. That is, the amount of brightness added by after-image or contrast depends upon the amount of brightness difference, respectively, between pre-exposure and color and surrounding field and color. As stated above this amount, when working in the dark-room, will be different for the different colors. For this reason and also because even the same amount of brightness excitation acts with different degrees of strength upon the comparative sensitivity of the retina to the different colors should be done in the dark-room. It should be done in a light room of a constant intensity of illumination and with pre-exposure and surrounding field in each case of the brightness of the color to be used. In this way alone can all the factors which influence the sensitivity of the retina, extraneous to the source of light, be eliminated.

colored and gray papers (*e. g.*, the papers of the Hering series) may be used on a color mixer.⁴ If, on the other hand, it is desirable to use the light of the spectrum or the light transmitted through standard filters, the colored light may be cut down to the threshold value by means of a sectored disk, the sectors of which should be covered with a gray of the brightness of the color at or near its threshold value. (2) For brightness discrimination also the threshold or limen test is the most sensitive and practical, but when made in a well-illuminated room, it becomes in effect a test for a just noticeable difference. This test may be performed at different points in the brightness scale, *e. g.*, when the standard is black, near mid-gray, or white. As before, disks of standard papers may be used on the color-mixer, or the light from a given source may be varied by means of a sectored disk.⁵ (3) Visual acuity tests of the Snellen type, especially when used in work in which it is required to make successive tests on the same person, are open to the following objections. (a) The judgment is in terms of recognition. A letter may be recognized when it is not seen clearly. In any judgment based on the recognition of even a single letter, memory plays an important role. It is, so far as the writer knows, impossible to standardize this memory factor and to obtain results strictly in terms of acuteness of vision. (b) The test card is made up of quite a long series of letters. As the test progresses the letters are memorized more and more completely. It is practically impossible to eliminate this progressive error when a number of successive judgments have to be

⁴ In making the tests with reflected light, two sets of disks are mounted on a color mixer (*a*) an outer disk of gray of the brightness of the color to be used, and (*b*) an inner disk made up of this gray and the disk of color. To the inner gray disk, varying proportions of the color are added until the threshold value or just noticeable color is obtained. To facilitate the judgment of just noticeable color, the inner disk of gray plus color is compared with the outer disk of gray as a standard. Since both grays are of the brightness of the color, the addition of the colored sector to the inner disk produces no change of brightness either to confuse the judgment of noticeable color, or to affect the intensity of the color excitation actually aroused. In getting the threshold value, the method of ascending and descending series should be used, that is, beginning with equality, the variation is towards noticeable difference and beginning with a difference greater than noticeable, the variation is towards equality. An average of the two sets of results is taken for the threshold value.


⁵ When the test is made with reflected light two sets of disks, an outer and an inner, are mounted on the color mixer. Each set is made up of one white and one black disk. Both sets of disks are set at the point in the brightness scale from which the variation towards white or black is to be made. One is kept constant and the other is changed until the judgment different is given. In making the judgment the method of ascending and descending series is used and the results are averaged for the difference limen. This difference limen is taken as the measure of the observer's sensitivity to brightness or white light.

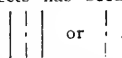
made as is the case before a final result is reached in any single visual acuity test and as is especially the case when a number of successive tests have to be given to the same person, which happens in much of the work involved in the solution of the problem here proposed. It might be supposed that the memorization of the series could be broken up by using in each successive judgment in a single test or in the successive tests, as the case may be, cards having a different distribution of the letters in the series. Considerable inconvenience would, however, be involved in giving the tests in this way and besides no guarantee could be had that each judgment would present the same degree of difficulty. That is, the series is made up of similar and dissimilar letters. The dissimilar letters can be distinguished from each other with less difficulty than the similar. It is practically impossible to distribute the letters so that the individual tests may be equally rigorous. This objection can, of course, be eliminated in part by a careful selection of the test letters, but not entirely because a series of letters uniformly similar cannot be found. (c) The Snellen series contains quite a large number of letters. The eye is found to fatigue and vision to blur before the series is completed. This introduces an error which it is practically impossible to render constant.

All of the above objections were eliminated in the tests finally adopted by us by changing the type of judgment and by making the test object in one case two parallel vertical lines stamped 1 mm. apart on a white card⁶ and in another the letters li printed in small type.⁷ In using these cards the observer's acuity of

⁶ The card is mounted on a sliding carrier which runs on a track made of two meter rods fastened end to end on a folding base. The base is mounted on adjustable stands fastened to a table. When making the test the apparatus is so adjusted that the track carrying the test card is just below and close to the observer's eye. In order that the observer's head may be held steady he is required to bite an impression of his teeth, previously made and hardened in wax on a mouth-board, which is rigidly fastened by a heavy iron rod and accessories to the table supporting the track and carrier.

⁷ Besides the letters li the writer would recommend the following figures as test objects.

(1) . The test is to distinguish clearly the dot at the center. A test object in the shape of a cross has the advantage of affording a steady control of fixation. According to photographic records of involuntary eye-movement, where a variety of fixation objects has been used, the cross is found to give the best control of fixation.

(2) . In these figures also the test is to distinguish the dot clearly. The former figure, however, is a little too complicated. There is both a tendency to lose the dot and for the lines to run together on either side. A simpler criterion gives an easier and safer judgment. Doubtless with a little effort other figures can be found possessing still greater merit as test objects.

vision is determined by the distance at which he can just clearly distinguish in every detail the two test objects. The results are thus rendered directly in terms of clearness of vision, and there are no progressive errors introduced by memory and fatigue.

We have good reason to believe that the brightness sensitivity, color sensitivity, and visual acuity tests rendered sensitive and adapted to our purpose in the manner described above will serve as a measure of the general level of efficiency of the unfatigued eye under different systems of illumination. For example, they show considerable difference in result when the tests are given under three types of lighting now in use: namely, systems of direct lighting, systems of indirect lighting, and daylight. In each of these cases, the intensity of the light falling on the test object measured in foot-candles is kept the same. The tests can not, however, be depended upon to show a loss of efficiency of the eye as a result of three or four hours of work even under a very unfavorable lighting system.

III. LOSS OF EFFICIENCY AS THE RESULT OF A PERIOD OF WORK.

We have no reason to believe that the brightness and color sensitivity tests have failed to show that the eye loses in efficiency as the result of a period of work under an unfavorable lighting system because of any fault in the tests. The tests used are the product of several years of study by the writer of the sensitivity of the eye to brightness and color and of the factors that influence this sensitivity. There is doubtless very little, if any, loss of sensitivity during this length of time. In fact it is commonly believed that the brightness and color processes are compensating in nature. The case is quite different, however, with the conventional visual acuity test, or even with the modification of it described above. Although brightness and color sensitivity are factors influencing the visual acuity test, still in every case to which it may be applied, it is predominantly a test of the refracting mechanism of the eye and its muscular control. In fact our results for the tests of brightness and color sensitivity teach us that when applied to the case in hand in which there has been no change in the quality and intensity of the illumination or of the refracting mechanism from the beginning to the close of work,

the results of the visual acuity test may be ascribed practically entirely to changes in the muscular control of the refracting mechanism, or at least to changes in the muscular control of the eyes as a whole.⁸ Now the visual acuity test, when it is confined to a momentary judgment of clearness of vision, is not adapted to show a loss in muscular efficiency because, although this efficiency may have been lowered enormously, it may rise momentarily under the spur of the test to its usual level, or at least to the level obtaining at the beginning of work. Just as the runner may, under the spur of his will, equal in the last lap of his course the highest speed he has attained at any other point in the course; so may the flagging muscles of the eye be whipped up to their normal power long enough to make the judgment required by the visual acuity test. It was the feeling of all our observers that at the close of work under the system of direct lighting installed in our laboratory the eye had lost heavily in efficiency. A great deal of discomfort was felt. The test was painful and was accomplished only with decided strain. Still the judgment could be made apparently with as much accuracy as at the beginning of work. But just as the runner finishing his course cannot long keep up his extra burst of speed, so might we expect that the eye cannot sustain its extra effort. This analogy led the writer to continue the visual acuity test through an interval of time. After considerable experimentation an interval of three minutes was chosen as best suited for our purpose. Our surmise proved to be correct. The fatigued eye cannot keep up its extra effort. The results of the test showed an enormous loss of efficiency as

⁸ Before the writer would speak with full certainty, however, that the retina loses none of its power to function for color and brightness sensation during the above stated period of work, he would feel it necessary to perform another kind of test for color and brightness sensitivity. This test has been devised by him especially to meet the needs of this problem. In this test the element of time is introduced. It is possible that the retina may have lost in power to give color and brightness sensation as the result of a period of work even when the conventional test based on a momentary judgment, shows no loss of sensitivity. That is, it may be more susceptible to fatigue as the result of the preceding work. To determine this, a fatigue test should be run at the beginning and close of work. For color this may be done in two ways. (1) A given amount of colored light may be used and the time required for the eye to become completely exhausted or insensitive to this color may be determined. The difference in time required for this amount of fatigue to take place at the beginning and at the close of work will represent how much the retina has lost in its power to function for color. (2) The experiment need not be continued until complete exhaustion takes place. The amount of exhaustion that has taken place in a given interval of time can be measured. As before, this can be done at the beginning and at the close of work and the results can be compared to find out how much the retina has lost in power to give color sensation.

the consequence of three hours of work under the system of direct lighting, while in daylight practically no loss was shown.

In detail the test is as follows. When the observer is required to look at the test card for three minutes, the test objects, even when the eyes are fresh, are not seen clearly for the whole time. The muscular effort required to keep the eyes adjusted for clear vision cannot be sustained steadily for that length of time. The test objects are seen alternately as clear and blurred. The time they are seen clear and blurred is recorded on a rotating drum upon which a line registering seconds is also run. From this record the ratio of the time seen clear to the time seen blurred is determined. This ratio may be fairly taken as a measure of the efficiency of the eye at the time the test is taken. In applying the test to our problem the record is taken at the beginning and at the close of work, and the ratios of the time clear and the time blurred are compared for the two cases to determine how much the eye has lost in efficiency as a result of work. Two values were chosen for the distance at which the test card was placed from the eye: (a) the maximal distance at which the test objects could be seen clearly in the momentary judgment, and (b) a distance less than this. The latter distance was chosen because for the maximal distance towards the close of the test, even when the eyes were fresh, the value of the time blurred became, it was thought, excessively high. Results for the two distances, therefore, give probably a fairer expression of the loss in efficiency than for the one.

The problem dealing with loss of efficiency as the writer has conceived it presents two phases. We may investigate (a) whether the eye shows a loss of efficiency after three or four hours of work under a given lighting system, and (b) whether there is a progressive loss of efficiency in working several months or years under a given lighting system. Only the first part of this investigation has been attempted thus far in our work and it has been undertaken, not so much for the purpose of making an exhaustive study of loss of efficiency under a given set of conditions, as it has been to get a sensitive and practical method of detecting loss of efficiency. In order to determine whether the method we have described is practical and sufficiently sensitive for our purpose, tests should be made on a

large number of people under a wide range of lighting conditions. We have not as yet made tests under a wide range of lighting conditions. We have chosen rather to begin with three broad types of illumination now in general use; systems of direct lighting, systems of indirect lighting, and daylight. Types based upon the distribution of light have been selected because it has seemed to the writer, both from his own work and from a survey of the work done by others, that distribution or diffuseness of light is the most important factor we have yet to deal with in our search for conditions that give minimum loss of efficiency and maximum comfort in seeing. The quality of the light and its intensity at the source are already pretty well taken care of, apparently at least better taken care of in general practise, relative to their importance to the eye, than is distribution. A detailed report of our results will not be given in this paper. The following results selected as typical from a large number of observations are appended, however, to show how the efficiency of the eye as measured by the above test falls off as the result of three hours of work under a system of direct lighting as compared with daylight.

The tests were conducted in a room 30.5 feet (9.29 m.) long, 22.3 feet (6.797 m.) wide and 9.5 feet (2.895 m.) high. The daylight illumination came from six windows, all on one side provided with thin white curtains to secure the necessary control. The artificial lighting⁹ was accomplished by means of two rows of fixtures of four fixtures each. Each row was 6 feet (1.828 m.) from the side wall and the fixtures were 6 feet apart. Each fixture was supplied with two 16 candle-power carbon lamps 29 inches (0.736 m.) from the ceiling with a white porcelain reflector 16 inches (0.406 m.) in diameter fastened directly above. The daylight tests were made at 9 A. M. and 12 M. Between these limiting times, the observer was required to read pages of type, uniform in size, printed upon paper of uniform texture of surface and of uniform reflecting power. The tests for the system

⁹ This room gave the impression of being brilliantly lighted. The writer was amazed to find, however, that only 2.5 foot-candles of light were received on the test card placed about midway between two of the rows of lights and midway between two sets of fixtures. The walls and ceiling of the room were of plaster, natural finish, and the floor of dark tiling. Before our tests were taken, the walls and ceilings were painted white which nearly doubled the light received on the test card.

of direct lighting were taken at 7 P. M. and 10 P. M. During the interval intervening, the observer was required to read type of the same size and printed on the same paper as was used in the daylight work. The reading was done in each case at exactly the same spot in the room as at which the tests were made. The intensity of illumination was also in both cases made as nearly equal as it was possible to do by methods now available.¹⁰ The two tests were always given on successive days but one. In order to guarantee that the observer's physical and optical condition should be as nearly the same for the two tests as it was possible to obtain, he was required to rest during the day immediately preceding each test. Since the li test has proven to be the more sensitive, results will be given for it alone in the following table. Column 1 of this table gives the time of day at which the work was done and the tests were made. Column 2 gives the type of test. Column 3 gives the distance of the test card from the eye. As stated earlier in the paper, two distances were used; one the maximum at which the test object could be seen clearly, the other a distance less than this. Division A of the table gives the results for the former distance; division B, for the latter. Columns 4 and 5 respectively, give the number of times the test object was seen clear and unclear. Column 6 gives the number of seconds in the three minutes that the test object was seen clear, and

¹⁰ In order to equalize the intensity of illumination, a method of measurement is required. Two methods were used by us; photometry, and a more delicate method based upon the sensitivity of the peripheral retina to brightness contrast. In case of the former, a Sharp-Millar portable photometer was used. The light falling upon the test card was measured in foot-candles and was made equal for each type of lighting. Full details of the latter method will not be given here. As stated above it is based upon the extreme sensitivity of the peripheral retina to brightness contrast, especially to the induction by a white screen. To apply the method, some given illumination is taken as standard. The amount of black induced by a white campimeter screen upon a 15 mm. area of some medium gray, (*e. g.* Hering gray No. 14) at an excentricity of 25 deg. in the temporal meridian, is measured. This amount of contrast is taken as the index of that illumination. To duplicate the illumination at any succeeding time, the intensity is varied until the same amount of contrast is induced by the white screen on the gray at the 25 deg. point, for the same observer. This method was devised in the writer's laboratory and he has found by repeated trials that, although it is not so convenient for many of the purposes for which the photometric method is used, it is many times more sensitive than the traditional photometric method. The Sharp-Millar photometer, like other photometers, is insensitive for the determination of the illumination of a room by daylight. This is because the standard field illuminated by the tungsten lamp is deep orange in color, while the comparison field illuminated by daylight is clear white. This difference in color tone makes the judgment of brightness equality difficult to make and renders the instrument extremely insensitive for daylight work.

column 7 the number of seconds unclear. Column 8 gives the ratio of the total time clear to the total time unclear. This ratio as stated earlier in the paper expresses the efficiency of the eye for clear seeing for an interval of three minutes at the time at which the test was taken.

TABLE I.

Showing How the Eye Falls Off in Efficiency as the Result of Three Hours of Work under a System of Direct Lighting as Compared with Daylight. In Division A the Test Card is Put at the Maximal Distance at Which the Test Object Could be Seen Clearly; in Division B, at a Distance Less than This.¹¹

	Time of day	Test	Distance of card from eye cm.	Number of times clear	Number of times unclear	Total time clear sec.	Total time unclear sec.	Total time clear ÷ Total time unclear
A.								
	9 A. M.	li	102	15	15	105.6	78.4	1.4
	12 M.	li	102	15	14	103.1	76.9	1.33
	7 P. M.	li	75	18	18	119.7	60.3	1.98
	10 P. M.	li	75	15	15	55.4	124.6	0.44
B.								
	9 A. M.	li	92	14	13	136.8	43.2	3.16
	12 M.	li	92	12	12	134.9	45.1	2.99
	7 P. M.	li	65	24	23	141.8	38.2	3.7
	10 P. M.	li	65	17	17	75.5	104.5	0.72

¹¹ It will be noticed in the table that the ratio total time seen clear ÷ total time seen unclear is smaller for the test both at the beginning and at the close of work in division A where the maximal distance at which the test object could be seen was used, than in division B where a distance less than this was used. This is just what should be expected from the nature of the test. For it may be said that, within limits, the nearer the object is to the eye the greater is the proportion of time it should be seen clearly; and, conversely, the farther the object is from the eye the smaller is the proportion of time it should be seen clearly. It will also be noticed that the ratio is slightly larger when the tests are made under the system of direct lighting than when made under daylight. The explanation of this, too, is found in terms of the distances that were chosen for the test object. These distances, relative to the maximal distance, were chosen shorter for the artificial light than for daylight. This was done because of the large falling off in the ratio gotten for the test at the close of work under the artificial light. Had the first of the two distances used in these tests, for example, been chosen as near to the maximal distance for the artificial light as it was for daylight, the result of the test made at the close of work would have been that, after the first interval seen as clear, the test object would have been seen unclearly during the remainder of the test. At first glance one might be tempted to think that the difference in the scale of magnitude for the two ratios, is due to some inequality in the intensity of the illumination that was given by the two systems of lighting. It is obvious on reflection, however, that the intensity of illumination can have little or nothing to do with the scale of magnitude of these ratios. The intensity of the illumination influences the maximal distances at which the test object can be seen clearly but the scale of magnitude of the ratio, time clear to time unclear must depend primarily upon how near the distance chosen for the test object is to the maximal distance. (This principle, it is obvious, does not affect the comparison of the ratios obtained at the beginning and close of work under a given lighting system for the dis-

(Continued on following page.)

In order to give a typical representation in graphic form of the effect of three hours of work on the efficiency of the eye in daylight and under the system of direct lighting, estimated in terms of the test we have described, the results of the above table are given in the form of a curve. In constructing this curve the length of time of work is plotted along the abscissa and ratio of the time the test object is seen clear to the time unclear, is plotted along the ordinate. Each one of the large squares along the abscissa represents an hour of work, and along the ordinate an integer of the ratio. Figure I shows the result of division A and figure II for division B of the table. An inspection of these

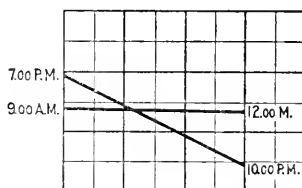


Fig. I.—Curve for division A of the table. Showing how the eye falls off in efficiency for three hours of work under a system of direct lighting as compared with daylight.

curves shows that the efficiency of the eye measured by the ratio of the time the test objects are seen clear to the time seen unclear, falls off rapidly for the system of direct lighting but scarcely at all for daylight.

Although it has been the purpose of this paper merely to out-

tance, once it is chosen for that system, is kept the same or both tests). As further proof that the difference in the intensity of illumination had nothing whatever to do with this result, the intensity of illumination was carefully determined immediately before and after these tests and, if the readings showed any inconstancy in the illumination, the results were discarded and new tests were made. The above explanation should be borne in mind also in examining the curves plotted from the results of the table. The curve for division B of the table, for example, begins at a higher point on the ordinate than for division A; and the curve for the artificial illumination starts at a higher point than the curve for daylight.

It is scarcely necessary to point out that neither the scale of magnitude of ratio nor the point at which the curve starts is of any considerable consequence for our work. The important thing is not how large is the ratio at the beginning of work, but how much it falls off as the result of work. In fact the magnitude of ratio need not be taken into account at all any further than that it chances to be a coincident result of a condition that seems to render our test more sensitive. That is, our results seem to show that the ratio falls off more when the distance chosen for the test object is not too near the maximal distance. In future work, therefore, more care should be taken probably than was exercised in this preliminary study to choose the distances for the test object so that in case of each lighting system employed they shall sustain the same ratio to their corresponding maximal distances.

line and in part to demonstrate a set of tests, a word of discussion and interpretation of the results we have reported may not be out of place here. Since the visual acuity test (given under constant quality, intensity and distribution of light) is a test largely of the refractive mechanism of the eye and its muscular control and since the refractive mechanism could not have changed during three or four hours of work, the obvious indication of the above result is that the loss of efficiency sustained by the eye in these experiments is a loss in muscular efficiency. This conclusion is borne out also by the fact, stated earlier in the paper, that the direct tests of the efficiency of the retina, namely, the test for brightness and color sensitivity did not show conclusively any loss.¹² Moreover, the conclusion is in line with current conception. In current theory the retina is considered as a mechanism more or less compensating in its action, while

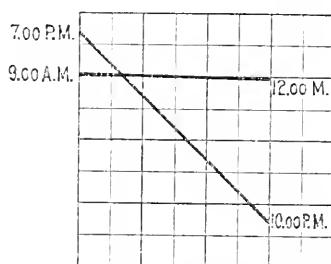


Fig. II.—Curve for division B of the table. Showing how the eye falls off in efficiency as the result of three hours of work under a system of direct lighting as compared with daylight.

the muscles of the eye are not so considered. The following reasons are suggested why the muscles of the eye giving both fixation and accommodation should be subjected to a greater strain by the system of direct lighting than by daylight. (1) The bright images of the electric bulbs falling on the peripheral retina which is in a perpetual state of darkness adaptation as compared with the central retina and is therefore extremely sensitive in its reaction to such intensive stimuli, sets up a reflex tendency for the eye to fixate them instead of the letters which the observer is engaged in reading. (2) Likewise, a strong reflex tendency to accommodate for these brilliant sources of light all at differ-

¹² This statement is also subject to the foot-note appended to the earlier statement.

ent distances from each other and from the lettered page, is set up. (3) These brilliant images falling upon a part of the retina that is not adapted to them causing as they do acute discomfort in a very short period of time,¹³ doubtless induce spasmodic contractions of the muscles which both disturb the clearness of vision and greatly accentuate the fatiguing of the muscles. The net result of all these causes is excessive muscular strain which soon shows itself as a loss in power to do work. In the illumination of a room by daylight with a proper distribution of windows, the situation is quite different. The field of vision contains no bright sources of light to distract fixation and accommodation and to cause spasmodic muscular disturbances, due to the action of intensive light sources upon the dark adapted and sensitive peripheral retina. In daylight the light waves have suffered innumerable reflections and the light has become diffuse. The field of vision is uniformly illuminated. The illumination of the retina, therefore, falls off more or less uniformly from fovea to periphery as it should in order to permit of fixation and accommodation for a given object with the minimum amount of strain.

It is not our purpose to contend in this report that distribution is the only factor of importance in the illumination of a room. The intensity and the quality of the illumination must also be taken into consideration. To test the relative effect of these factors upon the working power of the eye, records would have to be taken when each was varied in turn and the other two maintained constant. In the results shown in the above tables the intensity alone was constant in the two cases. Both the quality and the distribution were different in the direct lighting system and the illumination by daylight. The difference in the results obtained will have, therefore, to be attributed both to

¹³ There is no doubt in the writer's mind that the eye-discomfort experienced as the result of work under an unfavorable system of lighting is not by any means all muscular. The "sandiness" passing over into a stinging, stabbing pain which comes early in the experience of discomfort seems to be conjunctival. And while the retina itself is apparently insensitive to pain from mechanical stimulation, still when exposed to a source of light of a brilliancy to which it is not adapted, a painful reaction is produced which can scarcely be considered muscular. For example, after confinement for some time in a dark-room exposure to ordinary daylight is painful to the normal eye. That this is not entirely muscular can be shown by the fact that a similar reaction is experienced when the ciliary and iris muscles are paralyzed by atropine. The reaction is also experienced by aphakial subjects whose lenses have been so long removed that muscular atrophy must have taken place.

difference in the distribution and to difference in the quality of the illumination. In our tests comparative of the systems of direct and indirect lighting, the results of which will be reported in a later paper, clear tungsten lamps will be used in both cases. The intensity will be made the same and the quality of the light will be approximately the same. The distribution or diffusion alone will be different. Whatever difference in result we get in these two cases can, therefore, with reasonable certainty be attributed to the differences in the distribution of light.

With regard to the effect of varying the intensity of illumination, our results show nothing; with regard to the effect of varying quality, nothing in isolation; and with regard to distribution, we have data only for such differences as are found in the three types of illumination now in general use. In later work, however, the analysis along these lines will be completed. We hope on the laboratory side, to make a systematic study of the effect of wide ranges of variation of each of the factors in turn. It will be comparatively easy, for example, to keep the intensity and distribution constant and vary the quality, or to keep the quality and distribution constant and vary the intensity. We hope in addition, to supplement this work by testing the eyes of employees who work under a given lighting system for several hours a day, for evidences of a progressive loss of efficiency.

IV. A PRELIMINARY STUDY OF THE CAUSES OF DISCOMFORT.

In addition to studying the conditions that give us maximal efficiency, it is important to determine the lighting conditions and eye factors that cause discomfort. In fact, it might well be said that our problem in lighting at present is not so much how to see better as it is how to see with more comfort and with less damage to the general health on account of eye strain. Any comparative study of the conditions producing discomfort necessitates a means of estimating discomfort. It is obvious that the core of the experience of discomfort is either a sensation or a complex of sensations. As such, it should have a limen or threshold value just as other sensations have; and just as we are able in general to estimate sensitivity in terms of the threshold value, so should we in this case be able to use the threshold

value in estimating the eye's sensitivity or liability to discomfort under a given lighting condition. Threshold values are usually determined by finding how much energy or intensity of a given stimulus applied for a short interval of time is required to arouse a just noticeable sensation. This form of procedure, however, is not adapted to the needs of our problem. It is much better to reverse the process and find how long the eye has to be exposed to a stimulus of a given intensity to arouse just noticeable discomfort. Our limen, then, becomes a time limen, and is measured in units of time instead of in units of intensity. In order to determine whether the judgment of the limen of discomfort can be made with certainty and to test in general the feasibility of the method, the writer undertook to determine the comparative sensitivity of the eye to discomfort when the source of light was exposed in different parts of the field of vision. In order to carry out this investigation, a 16 candle-power lamp was attached to the arm of a perimeter in such a way that the end of the bulb was always directed towards the observer's eye. The arm of the perimeter could be shifted to any meridian in which it was desired to work, and the lamp could be moved at will along the arm. It was thus possible to expose the light at any point in the field of vision that was desired. Working in this way, we have investigated the effect of many types of variation of the distribution of the light in the visual field, and it is our purpose to extend the investigation as fast as possible to the variation of the other factors. Of the variations we have made in the distribution of the light in the field of vision, it will be necessary, however, in order to illustrate the general method of working, to describe only one, namely, the exposure of the source of light at different points in the field of vision for one eye when fixation and accommodation were taken for a far point.

In carrying out the investigation, the following precautions were observed. (a) It was found better to work in a room moderately illuminated by a source of light behind the observer and entirely concealed from him rather than in the dark. The intervals of dark-adaptation between exposures in the dark-room seemed to make the observer's eye too sensitive for our purpose. This was especially true for certain parts of the peripheral retina.

In becoming supersensitive there was a tendency to become erratically sensitive. (b) It was found that blinking serves as a variable factor for the relief of discomfort and that the amount of blinking must be made constant from test to test. This was accomplished by having the observer blink at equal intervals during the exposure, timing himself by the stroke of a metronome. The interval most natural and suitable for this purpose was determined for each observer separately. (c) All comparisons were planned in series. For example, if it were desired to compare the sensitivity of the temporal and nasal halves of the retina in a given meridian, the exposure was first made at a given point in one half and next at the corresponding point in the other half. This was to guarantee that the eye should be as nearly in the same condition with regard to progressive fatigue, etc., as was possible. Further to safeguard against error in this regard series were compared in which the exposures were repeated in the reverse order. (d) An interval of recovery was allowed between exposures. This interval had to be determined separately for each observer and often had to be made different for the same observer on different days. It was never changed, however, during the course of an experiment, the results of which were to be compared. (e) In order that the observer's head be held rigidly in position during the exposure, he was required to bite an impression of his teeth previously made and hardened in wax on a mouthboard. When an exposure was to be made, the fixation was taken, the light turned on, and a signal was given by the observer when a just noticeable discomfort was aroused, or, if it was desired, when the different stages of discomfort were reached. The judgment was found to present no especial difficulty, and the method, when properly applied, to provide a feasible means for comparing the sensitivity of the eye to discomfort under all the conditions to which we have been able thus far to extend its application. In actual practise the method also brings out an analysis of discomfort.

Discomfort seems to be a complex of three experiences, each of which develops at a different time. When the light is turned on, we have at once glare. This is a light sensation and though unpleasant has no painful elements. Next comes a conjunctival sensation

which begins with what is commonly called "sandiness" and soon passes over into a sharp, stinging, stabbing pain. Lastly there comes what is probably a muscular discomfort,—a hurting and aching in the ball of the eye which if the exposure is continued long enough seems to radiate to the socket and the surrounding regions of the face and head, the arch of the brow, the forehead, the temples, etc. Details will not be given here of the comparative sensitivity of different points of the retina to discomfort. It will be sufficient to say, that the periphery of the retina is more sensitive than the center; that the nasal half is in general more sensitive than the temporal half and the upper half than the lower half; and that in passing from the center to the periphery of the retina, the sensitivity is found first to increase then to decrease, becoming extremely little at the limits of the field of vision. In the horizontal meridians both on the temporal and nasal sides, maximal sensitivity is found around the 45 deg. point. In the vertical meridians, maximal sensitivity seems to be near the point 15 deg. below the horizontal. In a paper soon to be published, a detailed statement and explanation of these results will be given.

DISCUSSION.

DR. H. E. IVES: This paper is well worth the while of professional psychologists to study; and it gives to the illuminating engineer results which are extremely valuable.

When the illuminating engineer has the problem of producing satisfactory results, he has two methods of doing so; first, the case system, in which he copies an illumination produced by nature or invention, which has proved satisfactory by experience; and he hopes to get the same result. But there are defects in this method; we are very apt to follow the example of the Chinese who made motors by copying the imported ones even down to the color of the paint on the casings and the scratches on the paint. We may do equally foolish things by slavish copying. That is inherent in the case system. Up to recently some of us have been of the opinion that even with the defects of this case system we could apply it to advantage, for instance by studying how nature produces her lighting schemes. But in order to make any great

progress we must deviate from what exists; we must experiment and invent. This necessitates some means of testing our results and this process of experiment and test constitute the second procedure. Our Society has lately been interested in the physiological side of illumination, but has been sadly handicapped by the lack of significant tests—we have been dependent practically on laboriously acquired experience. One great object in adopting a method of measurement is the saving of time. For instance, suppose our only means of measuring voltage was by the duration of physiological disturbances following an electric shock. In order to duplicate a voltage which gives a shock whose after effects last a day, we would require weeks or months of toil, because of the time necessary to wait for the results of each experiment. Suppose the first time we secured the desired voltage we had an instrument known as a "voltmeter;" it would only take a minute to determine that voltage. We want something for measuring the effect of lighting systems which will enable us to get results with a speed comparable with that of a voltmeter.

Various methods of test have been proposed and Dr. Ferree has gone over all of these. He arrives at a conclusion which I think it behooves us all to observe; namely, that these tests will show what he calls "the general level or scale of visual efficiency," but they are practically useless as tests of the *loss* of visual efficiency.

Here is a sentence which means a great deal "Just as a runner may, under the spur of his will, equal in the last lap of his course the highest speed he has attained at any other point in the course, so may the flagging muscles of the eye be whipped up to their normal power long enough to make the judgment required by the visual acuity test."

Dr. Ferree here gives us the benefit of his point of view and experience in these matters. In this paper he has recognized the inefficiency of the methods now used. He realizes that we want a test of the *loss* of visual efficiency. The eye may respond momentarily, like the tired runner, and see the object as distinctly as before, but we know that it is not as efficient. Dr. Ferree has devised a test in which is introduced a time element. The observer views a visual acuity test object. When the

limit of visibility is found the observer is not allowed to rest, because he will again after an interval get just as good results as at first; instead he presses a key as long as the detail is clear; then when the tired muscles flag and the object blurs, the finger on the key is removed. At first it appears easy to see the detail clearly, but pretty soon it is not so easy and one does not distinguish the chart so well. Very soon it becomes necessary to take the finger off the key. Intervals of clear and blurred vision alternate and at the end we have a ratio of the time the chart is distinguishable to the time when it is not.

Dr. Ferree has tried out daylight and a direct artificial lighting system and we have here for the first time the results of that test. They show what many of us have been sure of; that daylight does not decrease the efficiency nearly as much as artificial lighting. On the fourteenth and fifteenth pages are two charts showing by straight lines the falling off in efficiency which occurs under artificial lighting as compared to daylight. Personally, I think we should say "Eureka!"

I hope Dr. Ferree will proceed to standardize these tests and tell us the best working distances and one thing and another. As he is not here, I have tried to bring out the most important points. He has given us a most valuable contribution, and I hope before long we will be in a position to settle these questions of light and dark walls by this method of test and not by "Kilkennycat" discussion, which brings us nowhere.

I think we should do our best to aid Dr. Ferree to develop this method of test to give us what now we can get only by experience. I am aware that I have not done this paper justice, but I want to express my appreciation of his work.

MR. C. O. BOND: The American Medical Association is a body whose conclusions as to the harmful or beneficial effects of any types of illuminating installations will carry considerable weight. They have discussed time after time how they were to make the tests, and this paper has grown out of Dr. Ferree's experiments, in the hope of placing in the hands of that Committee means of making the tests. We are extremely fortunate in having the first public report of this method. The method is under advisement by the Committee and I was present at one of their meetings when Dr. Ferree brought a set of this apparatus

to Philadelphia and they made a test of it. Two or three of the doctors present were very much impressed with it. I think, even if it does not succeed as it now stands, perhaps here is the germ of the best possible method of test.

DR. C. E. FERREE (communicated in reply): I can express only great appreciation of the interest that the men who have preceded me have taken in our work. The problem is extremely interesting to me and I hope we have here a vulnerable point of attack. Once we have procured a successful method of measuring the effect of different lighting systems on the eye, a broad field of application opens out before us. We not only can find out what are the favorable and what are the unfavorable features in a lighting system, but we can no doubt, as may be inferred from Dr. Ives' discussion, test out and perfect a lighting system, so far as its effect on the eye is concerned, before we put it on the market. This latter point is a good one, I think, and I thank Dr. Ives for the suggestion.* I feel that Dr. Ives' perspective and practical grasp of the situation is a distinct contribution to the paper.

We are very much handicapped at present for funds by means of which to carry on this work. In the first place apparatus and models of lighting systems are required for the work on the laboratory side. Trained assistants are also needed to help out with the details of the work. Further, to verify and enlarge the work done in miniature in the laboratory, we should test the eyes of employees working under established lighting systems and in the surroundings in which these systems have to operate. All of this takes time and money, also entrance into commercial concerns. In all of these regards we need the help and influence of the Illuminating Engineering Society.

This work, I suppose, could be done spontaneously and sporadically here and there as the insight and inclination of various men may direct. But in the beginning, at least, I do not think it should be scattered. Until launched and safely moving, it should be done under common supervision.

* The general idea that over and above its application to abstract investigation the test may have an application in the daily work of the lighting engineer has come to the writer by suggestion from the engineers themselves. Mr. Cravath, for example, has recently pointed out that the test should be of advantage in making the actual installation of a lighting system. The writer would suggest in addition that it may further be of service in determining the effect of different kinds of type and paper on the efficiency of the eye; also the effect of different kinds of desk lighting, etc. In short, it is obvious that the usefulness of such a test is limited along these lines only by its sensitivity.

THE FACTORS THAT INFLUENCE THE SENSITIVITY OF THE RETINA TO COLOR:

A QUANTITATIVE STUDY AND
METHODS OF STANDARDIZING

A Dissertation

PRESENTED TO THE FACULTY OF BRYN MAWR COLLEGE IN PARTIAL
FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE
OF DOCTOR OF PHILOSOPHY

BY
GERTRUDE RAND

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PREFACE.

The following study, practically as is here presented, was submitted to the Faculty of Bryn Mawr College in May 1911 in partial fulfillment of the requirements for the degree of Doctor of Philosophy. It is the outgrowth of a series of studies dealing with the phenomena of color vision that was begun in 1908 by the writer working under the direction of and in collaboration with Professor C. E. Ferree of Bryn Mawr College. In order to show in what way the present study, which deals with the formulation of a technique for investigating color sensitivity, is the logical outcome of the initial studies in the series, and is, moreover, required for the completion of the later studies, a brief résumé will be given of the work undertaken in the investigations preceding and following it.

The first of these studies entitled: *Colored After-image and Contrast Sensations from Stimuli in Which No Color Is Sensed*, was published in the *Psychological Review*, 1912, XIX, pp. 195-239. As is shown by the title, the article deals with the conditions under which colored after-image and contrast sensations may be aroused from stimuli in which no color is sensed. A formulation of these conditions, together with allied fusion and limen experiments, shows the phenomenon to be a peculiarity of the inhibitive action of brightness upon color. Brightness fused with color inhibits its saturation. With the exception of the region just within the limits of sensitivity for two colors, the following may be stated roughly as a law of this action for all colors and all parts of the retina: white inhibits most, grays in the order from light to dark next, and black least. This law was generalized from the results of fusion and limen experiments in a large number of meridians of the retina. In accord with this law, color may be obtained in the after-image when none is sensed in the stimulus when an unfavorable brightness quality is fused with the stimulus color and a favorable one with the after-image color. The technique for securing these conditions

for the after-image sensations in central and peripheral vision, for the contrast sensations in central vision, and for the phenomenon which we have called the Purkinje-Brücke phenomenon, is described in detail in the paper. But the study is not quantitative. The results do not show, for example, that the inhibition of the stimulus color has no effect upon the after-image. They show merely that, working near the limen, the stimulus color may be inhibited and the complementary color still be sensed in the after-image.

In order to determine as accurately as possible to what degree, if at all, the intensity of the after-image excitation is decreased by adding to the stimulus color a brightness excitation unfavorable to its saturation, the second study of the series was begun in 1909. It was entitled: *The Fusion of Colored with Colorless Light Sensation: The Physiological Level at Which the Action Takes Place*. An abstract of this article was published in the *Journal of Philosophy Psychology and Scientific Methods*, 1911, VIII, pp. 294-297. The full report will shortly be published in the *Psychological Review*. The results of this study have a twofold bearing. (1) They make plain once for all why it is possible to obtain color in the after-image when none is sensed in the stimulus, for they show that the intensity of the after-image excitation is not decreased at all by adding to the stimulus color a brightness excitation unfavorable to its saturation. (2) They throw some light on the broader problem presented by the fusion of brightness and color. By serving to indicate the level at which this action takes place, they help, for example, to explain a number of somewhat puzzling phenomena attendant upon the fusion of brightness with color, in case of positive, after-image, and contrast sensations. This action takes place apparently posterior to the seat of the after-image and contrast processes and the cancelling action of the complementary colors. There are two effects of the fusion of brightness with color, both of which are pressed into service in drawing the above conclusion: (1) it reduces the saturation of the color sensation; and (2) it changes the quality or tone of certain colors. This conclusion is based on the following lines of argument:

(1) When the color of the stimulus is inhibited by the addition of a brightness excitation, the intensity of the after-excitation, judged in terms of the duration of the after-image, is not affected by this excitation. (2) When the tone of the color aroused by a given stimulus is changed by the addition of a brightness excitation, the color of the after-image does not undergo a complementary change. (3) When the saturation of the inducing color is inhibited by the addition of a brightness excitation, the saturation of the contrast color is not affected by the change. (4) When the tone or quality of the inducing color is modified by adding a brightness excitation, the tone of the contrast color is not determined in the complementary direction. (5) When a given color is inhibited by the addition of a brightness excitation, its power to cancel the complementary color is not altered. (6) When the tone or quality of a color is altered by the addition of a brightness excitation, the tone or quality of the color required to cancel it is not affected by the change. (7) When the tone or quality of a color has been altered by the addition of a brightness excitation, the color component added can not be cancelled by mixing with the original color a color complementary to this component. Since, then, this fusion affects the positive and not the negative excitation and does not affect the cancelling action of the complementary colors, the conclusion is drawn that it takes place at some physiological level posterior to the seat of the after-image and contrast processes and to the cancelling action of the complementary colors. This study deals, however, only with the measure of the effect of the fusion of brightness and color as it occurs in central vision.

In order to extend the investigation to the peripheral retina, a third study was begun in June 1911. Its object was as follows. (1) It was planned to determine the effect of the fusion of brightness with color at a number of points from the center to the periphery of the retina, and to see how far the following points can be explained in terms of this action: (*a*) the influence upon the limits of color sensitivity of the brightness of the surrounding field and of the preëxposure; and (*b*) the color changes that occur in passing from central to peripheral vision. (2) A

comparative study was to have been made of the chromatic and achromatic phenomena of the peripheral retina. Both of these sets of phenomena for the peripheral retina show a number of striking differences from the phenomena of the central retina. Some of these points of difference are as follows: (*a*) There is considerable difference in the action of the achromatic qualities on color. (1) They inhibit or reduce the saturation of color much more strongly in the peripheral than in the central retina. (2) Of the achromatic qualities, white inhibits all colors the most strongly and black the least strongly in the central retina, while near the limits of sensitivity in the peripheral retina, black inhibits red and yellow the most strongly and white the least strongly. (3) The change in the tone or quality produced by adding white or black is much more pronounced in the peripheral retina and is often in a different direction. For example, black added to yellow in daylight illumination in the central retina turns it towards green; while in the peripheral retina the change is towards red. (*b*) Varying the brightness of the surrounding field has more effect on colors in the peripheral than in the central retina. (*c*) Exhaustion to color takes place more rapidly in the peripheral than in the central retina, that is, the change of saturation per unit of time is faster. (*d*) The colored after-image is of very short duration in the peripheral retina, but in proportion to its duration, it is much more saturated than the after-image of the central retina. (*e*) Some of the differences with regard to the achromatic phenomena are as follows. There is a very strongly increased sensitivity to contrast and to flicker; adaptation or exhaustion occurs very rapidly; the after-image is quickly aroused, is relatively very intensive, and in proportion to its intensity lasts a very short time; and so on. These points of difference raise the question how far we need go in assuming a different mechanism for the two parts of the retina. The purpose of our investigation was to have been primarily to determine how many of these differences are due at least in part to the difference in the state of brightness adaptation of the central and of the peripheral retina. (3) Maps were to have been made showing the sensitivity of the eye to the different

colors for three kinds of background (white, black, and gray of the brightness of the stimulus color). These three backgrounds were selected because they represent the extreme situations with regard to achromatic induction: maximal black induction, maximal white induction, and no induction; and, therefore, represent the best conditions that can be obtained for the study of the effect of the brightness of the surrounding field upon the local sensitivity of the retina. A sufficient number of meridians were to have been worked over to give an accurate outline of the zones of sensitivity for the three kinds of background used. Gradients were to have been established showing the falling off in sensitivity from the fovea outwards. Also the changes in color tone were to have been determined from point to point for all the backgrounds. Both sets of determinations were to have been made by matching in central vision what is seen in peripheral vision. The object of this investigation was to have been to give a complete representation of the sensitivity of the entire retina, quantitative and qualitative, in terms that are more or less familiar to all, namely, the sensation values of the central retina. It was found, however, that the large M. V. occurring in the work from observation to observation rendered the extended comparative investigation planned impossible. The original plan had, therefore, for the time to be abandoned, and the present study was undertaken.

This study aims (1) to determine what are the factors that influence the sensitivity of the retina to color; (2) to make a quantitative examination of the factors extraneous to the stimulus; and (3) to provide methods for their standardization. For the sake of historical continuity, the study is preceded by an historical and critical résumé of the analyses of factors influencing color sensitivity that have been made up to this time and of the attempts to standardize. It may be stated in passing that with the control of factors rendered possible by this study, the original plan of work has been resumed and in part completed. It will be published in the near future.

There remains to be mentioned the relation of the present study to the final one of the series. The latter has developed

from the historical and critical résumé mentioned above of the investigations that have been made to determine the factors that influence the sensitivity of the retina to color. In the course of this discussion various deficiencies have been pointed out in the methods used by previous investigators in their attempts to control these factors, and ways have been devised to correct these deficiencies. The factors that influence the sensitivity of the retina to color may be divided into two classes: those pertaining to the stimulus, and those extraneous to the stimulus. The experimental part of the present study is especially directed toward making a quantitative estimate of the latter set of factors under various typical conditions obtaining in the investigation of color sensitivity and toward securing effective methods of control. No concern is had, however, to standardize the factors pertaining to the stimulus any farther than is necessary to accomplish this purpose. The more effective standardization of these factors will form the subject of our future work. The question of intensity will be taken up first. It has been shown in the historical part of the present study that this factor has been most inadequately handled by previous investigators. In determining the comparative sensitivity of the retina to the different colors, for example, either no account has been taken of the different intensities of the colors used, or incorrect methods have been employed of equalizing these intensities. In no case has the determination been made in terms of units that can be compared. It is the writer's purpose to make an exhaustive determination of the sensitivity of the retina to the different colors in terms of such units. The comparative limits of sensitivity will be determined in a number of meridians with stimuli equalized in energy, and the limens and the j.n.d's. of sensitivity at different degrees of intensity will be determined in terms of radiometric units at various points from the center to the periphery of the retina in the different meridians. This investigation in fact is now in progress. A preliminary statement of the plan of this work has already been published by the writer in collaboration with Professor Ferree (*American Journal of Psychology*, 1912, XXIII, pp. 328-332).

From the above discussion of the place of the present study in the series, it will be evident to the reader how extensively this study has been due to the instruction, guidance, advice, and assistance of Professor Ferree, and how great a debt of gratitude the writer owes him. In stating his share and collaboration in the studies preceding and following this in the series, I can indicate perhaps more fully than in any other way the share he has had both directly and indirectly in the production of the present study.



I. INTRODUCTION.

In no branch of psychological optics does one find such varied and contradictory results as in the work on the color sensitivity of the peripheral retina. This is doubtless due in minor part to the intrinsic difficulty of the indirect vision observation, but in major part it is due to the lack of adequate standardization of the factors that influence the local sensitivity of the peripheral retina. These factors may be divided into two classes: (*a*) those pertaining to the stimulus, or the source of light; and (*b*) those extraneous to the source of light. In the former class may be included the size, intensity, and brightness of the stimulus; in the latter, the preëxposure or what the eye has rested on before being exposed to the stimulus, the surrounding field, and the general illumination of the visual field.¹ The work of standardization thus far has been directed largely towards the factors in the former class. Of the factors in the latter class, attempts have been made, as will be shown later in the discussion, to standardize only the influence of surrounding field. The recognition of the importance of this factor came relatively late in the development of the technique of the subject. It was at one time thought that the use of the perimeter and the dark-room provided ideal conditions for testing the local sensitivity of the peripheral retina, because by this means the local area alone was stimulated by light, hence it was thought that the influence of the surrounding field was eliminated. We know now that these conditions were not so ideal as they seemed, that a dark- as well as a light-

¹ In case the colored light is obtained by reflection from a pigment surface, some exception may be taken to the above classification, for unless some especial device be used to illuminate the pigment surface, the intensity of the stimulus will depend upon the degree of the general illumination of the visual field, and the brightness of the stimulus will also, to a certain extent, be dependent upon the general illumination. In such a case, these factors would have to be included in both classes. If on the other hand the colored light is obtained by means of standard filters, or from the spectrum, the illumination of the visual field will exercise its influence entirely independently of any effect on the stimulus.

adapted retina influences by contrast the sensitivity of the area stimulated. The use of the perimeter and dark-room accomplishes, then, but a very small part of the purpose for which it was intended. Instead of eliminating altogether the influence of the brightness of the surrounding field, it makes only one phase of it constant. It standardizes by giving us one state of brightness-adaptation alone, namely, the adaptation of the dark-room.² The campimeter was devised especially to correct this deficiency. Its purpose is to control and standardize the influence of the brightness of the surrounding field when one is working with a light-adapted retina. But the campimeter, like the perimeter, has accomplished only in part the purpose for which it was intended. It standardizes the influence of the surrounding field for one degree of illumination only, because the influence of the campimeter screen changes markedly with changes in the illumination of the visual field. There are two reasons for this. (*a*) A brightness match between the colored stimulus and the gray of the surrounding field made at one illumination will not hold at another. And (*b*) the sensitivity of the retina to brightness induction changes markedly with changes in the general illumination. This latter point is especially true in the peripheral retina where changes which are too small to be detectable by any current photometric device produce quite a noticeable change in the amount of induction between two surfaces of different brightness. The campimeter, then, is almost useless as an instrument of precision, unless the general illumination can be rendered constant or some means can be devised for standardizing the observation for changes of illumination. No satisfactory method has as yet been obtained for keeping the illumination of a room by daylight constant. To keep it constant presupposes what has not as yet been provided, namely, a sensitive means of measurement. Constancy may be approximated by artificial illumination,

² As will be shown later in the paper, neither the influence of surrounding field nor of preëxposure can be eliminated when the observation is made in the dark-room. The influence of these two factors can be eliminated only by working in a light-room of constant intensity of illumination, and by using a preëxposure and a surrounding field of the brightness of the color used for the stimulus.

but no artificial source has yet been devised which gives a light that approaches average daylight³ sufficiently closely in composition to warrant its use in color work. Of the various sources of light the Moore Tube comes nearest to doing this, but spectrophotometric and colorimetric determinations show that the light from it contains an excess of blue⁴ and, therefore, although it has been adopted by various textile concerns for use in color matching, its substitution for daylight can scarcely be recommended for the more exact requirements of color optics. Ives and Luckiesh⁵ attack the problem of producing artificial daylight from another side. By their subtraction method they claim to have gotten the closest approximation to average daylight yet attained. They aim to cut out by absorbing screens the excess of red and yellow in artificial light due to the comparatively low temperature of artificial illuminants. Tungsten lamps are used by them as the source of light, and two kinds of commercial glass approximating in their absorptive action cobalt blue and signal green are used as screens. In order to correct for the pronounced band of yellow-green transmitted by the cobalt blue, a film of gelatine dyed with rozeine is also used. Although according to comparative measurements made by Ives and Luckiesh the light thus gotten is the closest approximation to average daylight yet obtained, still it shows a deficiency of 15% in the green and about 25% in the blue. Moreover, the spectrum of this light does not show the brightness distribution of the spectrum of daylight. Since the absorbing screens cut down the light emitted by the tungsten lamp to 15% of its original intensity, the spectrum of

³For results of measurements of the color values of average daylight, see Nichols, E. L. *Transactions of the Illuminating Engineering Society*, 1908, III, p. 301. Ives, H. E. The Daylight Efficiency of Artificial Illuminants. *Transactions of the Illuminating Engineering Society*, 1909, IV, pp. 434-442; Color Measurements of Illuminants. *Transactions of the Illuminating Engineering Society*, 1910, V, pp. 189-207.

⁴See Ives, H. E. Color Measurements of Illuminants. *Transactions of the Illuminating Engineering Society*, 1910, V, p. 206; and Rosa, E. B., quoted by Moore, D. McF. A Standard for Color Values. *Transactions of the Illuminating Engineering Society*, 1910, IV, p. 224.

⁵Ives, H. E. and Luckiesh, M. Subtractive Production of Artificial Daylight. *Electrical World*, 1911, LVII., pp. 1092-1094.

the light finally given out shows the brightness distribution characteristic of lights of low intensity, unless the original light-source is of extremely high candle-power.

We seem thus compelled either to give up the investigation of the sensitivity of the retina for daylight illumination, or to devise some means of keeping this illumination constant. At an early stage in the study of the color phenomena of the peripheral retina begun four years ago and still in progress in the Bryn Mawr Laboratory, the writer was compelled to take into account the influence of the changes in the illumination of the visual field upon the color observation. The changes of illumination that took place from day to day, the progressive changes during the day, and the many sudden changes even in the course of an hour, rendered any constancy, or close reproduction of results entirely out of the question. The consideration of this factor led in turn to a general study of the conditions that influence the color observation. It is the purpose of this paper to report the results of that study. The report will take the following form.

(1) A résumé and criticism will be given of previous studies of factors, and of attempts to standardize. (2) The color observation will be reexamined for the factors that influence its results, and a study of these factors will be made with the following points in view: (*a*) Their influence will be measured under various typical conditions obtaining in the work on color sensitivity. (*b*) Their effect on the limen of color at different points in the retina and on the limits of color sensitivity will be determined. (*c*) An explanation based on the conclusions drawn from (*a*) and (*b*) will be made of the results of other experimenters and of the contradictions found in these results. (3) From this study of the influence of the factors, it will be determined what factors need to be standardized in the various kinds of work on color sensitivity and methods will be devised for their standardization.

In the latter part of the work especial attention will be given to the effect of general illumination and of local preëxposure. The writer finds these to be the two most important factors extraneous to the source of light that influence the results of the color obser-

vation, and yet, so far as she is able to determine, up to this time no attempt worthy of more than passing consideration has been made to standardize either factor in investigations of color sensitivity. In fact, it can scarcely be said that either has been included in the list of factors by any previous writer. The effect of the general illumination has received only casual mention by Ole Bull and a few others, and the brightness of the preëxposure has not been clearly recognized as exerting any influence whatever.

II. HISTORICAL AND CRITICAL.

A. FACTORS THAT HAVE BEEN FOUND TO INFLUENCE THE SENSITIVITY OF THE RETINA TO COLOR.

1. *Size of the Stimulus.*

An increase in the size of the stimulus is generally considered to be equivalent in some proportion to an increase in intensity.¹ It is but natural, then, to think that an increase in the size of the stimulus would both lower the limen of sensitivity and extend the limit of the zone within which a given color can be sensed. The question with regard to the limits of sensitivity is, however, not so simple as it seems. In the first place, the limit of the zone may not be extended, because the retinal sensitivity may fall off so rapidly at the point worked upon, that the increase of stimulation is not sufficient to overweigh the loss. In the second place, the effect of the increase of area may depend to some extent upon the area of the original stimulus. For example, fatigue is set up so easily with very small stimuli that an increase up to a certain point is advantageous, while, on the other hand, the outer margin of large stimuli may extend so far into the zone of relative insensitivity that a further increase of area becomes ineffective. In the third place, the effect may vary with the meridian of the retina investigated. Two reasons may be assigned for this variation. (*a*) We should expect the effect to be in some measure proportional to the rapidity with which the retina falls off in sensitivity from the fovea to the periphery. For example, in the temporal and lower

¹ Raehlmann, E. Ueber Farbenempfindung in den peripherischen Netzhautpartien in Bezug auf normale und pathologische Brechungszustände. Inaug. Diss., Halle, 1872.

While the work of Raehlmann and others shows in general the truth of the above statement, no systematic determination of the exact relation of change of area to change of intensity has yet been made. This determination for the sensations aroused both by white and colored light is now in progress in the Bryn Mawr laboratory.

meridians, where the sensitivity falls off sharply, we should expect little if any effect; while in the nasal and upper regions, where the decrease is much more gradual, we should expect considerable effect. (*b*) In the nasal and upper meridians, the limits of sensitivity extend much farther toward the periphery than in the temporal and lower meridians. There is in these meridians, then, as the limits of sensitivity are approached, a relatively greater shrinkage in one dimension of the stimulus, owing to the greater angle of excentricity, than occurs in the temporal and lower regions. In proportion as this shrinkage causes a shortening of one dimension of the stimulus, it adds to the range of areas over which an increase is of advantage for extending the limit of sensitivity.

A survey of the literature on peripheral vision shows that the size of the stimulus was early recognized as one of the factors influencing the sensitivity of the peripheral retina. In fact, the first investigation of peripheral sensitivity was made to determine the effect of the size of the stimulus. This work done by Hueck² in 1840, may be considered as pioneer, for although Troxler³ and Purkinje⁴ had previously mentioned the phenomena of peripheral vision, they had made no systematic attempt to investigate these phenomena. Hueck's object was primarily to study the effect of increase in the size of the stimulus upon the limits of the field of vision. Using gray paper stimuli of very small area, he observed the effect on the limit of vision (*a*) when their objective size was increased, and (*b*) when their apparent size was altered by a decrease in their distance from the observer, that is, by enlargement of the visual angle. He found that an increase in size produced in either of these ways caused a widening of the field of vision for that quality of stimulus. The investigation was also extended to color. Pig-

² Hueck, A. Von den Grenzen des Sehensvermögens. Müller's Archiv, 1840, p. 95.

³ Troxler, D. Ueber das Verschwinden gegebener Gegenstände innerhalb unseres Gesichtskreises. Ophthal. Bibliothek herausgegeben von Himly u. Schmidt, Jena, 1804, I, 2. pp. 1-53.

⁴ Purkinje, J. Beiträge zur Kenntniss des Sehens. 1823, I, p. 76; 1825, II, p. 14.

ment papers were used. This investigation showed that the limits of color sensitivity also are influenced by the size of the stimulus. An interesting table was compiled which shows that by altering either the size of the stimulus or the visual angle it subtends, the limit of sensitivity can be made to vary by amounts equal to 1° over a wide range of the retina. Hueck's conclusion, that the limits of color vision are influenced by the size of stimulus, was confirmed by Aubert⁵ in 1865. Five years later it was contradicted by Woinow.⁶ Woinow worked in the dark-room, using for stimuli colored glasses illuminated by a shaft of sunlight of variable extent. He claimed that "die Grenze immer dieselbe ist, ohne Rücksicht auf die Grösse der Pigmentfläche, wenn die Gesichtswinkel nicht von der Mitte sondern von dem dem Auge zugekehrten Rande der Pigmentfläche berechnet werden." No information is given as to the size of stimuli employed. Krükow,⁷ repeating Woinow's precaution of measuring the angular distance to the inner edge of the stimulus rather than to the middle, confirmed the conclusion that the boundaries of the color zones are absolute, within certain limits of size of stimulus. His stimuli were 3, 6, and 9 mm. square. Aubert⁸ in 1876, repeated the observations recorded in his earlier work. Colored squares with sides varying from 1 mm. to 32 mm. placed at a distance of 20 cm. from the eye were used as stimuli. The results he obtained led him to believe that the size of the stimulus is a factor in determining the limits of sensitivity. He writes: "Die Grösse des farbigen Objectes massgebend ist für die Entfernung vom Centrum, in welcher es noch farbig empfunden wird. Die gegentheilige Behauptung Woinow's . . . muss ich nach vielfacher, wiederholter Untersuchung für falsch erklären." He mentions the precaution used by Woinow as to the measurement of the angular distance, but does not definitely state that he himself took this precaution. Raehl-

⁵ Aubert, H. *Physiologie der Netzhaut*. Breslau, 1865, p. 121.

⁶ Woinow, M. *Zur Farbenempfindung*. A. f. O., 1870, XVI, p. 219.

⁷ Krükow. *Objective Farbenempfindung auf den peripherischen Theilen der Netzhaut*. A. f. O., 1874, XX., pp. 255-296.

⁸ Aubert, H. *Physiologische Optik*. Leipzig, 1876, pp. 541-544.

mann,⁹ Schön,¹⁰ Schirmer,¹¹ and Briesewitz,¹² all agree with Aubert; but they also have not mentioned their method of measurement.

In Tschermak,¹³ however, we find an investigator who has observed Woinow's precaution and yet has obtained results that are contradictory to Woinow's. He investigated the factors which condition the colorless vision of the peripheral retina, and showed that neither the red-green nor the totally color-blind zones of the normal retina are invariable in extent. Size of stimulus was found by him to be one of the factors that determine the breadth of these zones. This he demonstrated on the Hering apparatus for investigating the color sensitivity of the peripheral retina, an apparatus consisting of a campimeter screen with an opening behind which the stimulus is placed. Tschermak's screen was of gray paper. The size of the stimulus-opening was regulated by means of two gray slides which widened the opening either on the side within the visual field and toward the fovea, or on the other side toward the periphery. Using a small stimulus-opening, he determined the degree of excentricity at which *Urgrün* and *Urroth* appeared colorless. He then widened the stimulus-opening toward the fovea and found that the color was sensed. No conclusion, however, can be drawn from this because he had extended the inner margin of the stimulus into the region sensitive to color, hence the sensation aroused may have been due to that cause rather than to the increase made in the area of the stimulus. He next widened the original stimulus-opening toward the periphery. This caused an increase in the area of the retina stimulated, without extending the margin of the stimulus into the field sensitive to color. Since in this case also the color was sensed, Tschermak concludes that the

⁹ Raehlmann, E. loc. cit.

¹⁰ Schön, W. Ueber die Grenzen der Farbenempfindung in pathologischen Fällen. Klinische Monatsblätter, 1873, p. 171.

¹¹ Schirmer, R. Ueber erworbene and angeborene Anomalien des Farbensinns. A. f. O., 1873, XIX, p. 194.

¹² Briesewitz. Ueber das Farbensehen bei normalem and atropischem Nervus Opticus. Inaug. Diss., Greifswald, 1873.

¹³ Tschermak, A. Beobachtungen über die relative Farbenblindheit in indirectem Sehen. Pflüger's Archiv, 1890, LXXXII, pp. 559-560.

limits of color sensitivity are influenced by the area of the stimulus. It is in the second method of increasing the area of the stimulus that Tschermak took the precaution mentioned by Woinow relative to the measurement of the angle of excentricity.

But it is obvious that the method of measurement need not have been the only cause of variable results in work of this kind. The meridian tested may have been, as we have already suggested, a second cause. That certain regions of the retina react differently to an increase in the area of the stimulus, is noted in a brief paragraph by Kirschmann.¹⁴ Using stimuli of 28, 40, and 58 mm. in diameter, he found that the color sensitivity of the peripheral retina is dependent to different degrees in different meridians upon the size of the stimulus. In the lower and temporal meridians, the zone sensitive to each color was widened very slightly by increasing the area of the stimulus, and never beyond certain limits. On the upper and nasal parts of the retina, however, the possibility of widening the zones by this means seemed to be, he says, unlimited. Now we know that Woinow and Krüchow obtained their results on the temporal meridian. Tschermak, however, does not state what region he investigated. If he worked in the nasal region, his conclusions may be reconciled with those of Woinow in the light of Kirschmann's work. These variations in the effect of area in different regions of the retina are no doubt due largely to the difference in the rapidity with which sensitivity falls off from the center to the periphery of the retina along the several meridians. Where the decrease is gradual, as is the case in meridians that have wide limits of sensitivity, more effect might be expected than where the sensitivity decreases rapidly.

A third cause of the variable results recorded may have been the range of size of stimuli employed. The retina fatigues easily to very small stimuli; hence an increase in size up to a certain point is advantageous. On the other hand, the margins of very large stimuli may extend so far into the zone of insensitivity that a further increase is ineffective. Krüchow no doubt

¹⁴ Kirschmann. A. Die Farbenempfindung bei indirectem Sehen. *Philos. Studien*, 1893, VIII, p. 612, 613.

referred to this fact when he said that color sensation is independent of the size of the stimulus, but only within certain limits. An interesting conclusion reached by Abney¹⁵ may also be mentioned in this connection. He wished to determine at what intensity the different colored spectral lights were brought below the limen of sensation both in central and at various points in peripheral vision. He found, however, that the intensity of the stimulus is not the only factor to be considered. A stimulus 2 inches in diameter, for example, was seen at a lesser intensity than a stimulus $\frac{1}{2}$ inch in diameter. He further found that it is not the area, but the shortest dimension of the stimulus, vertical or horizontal, which determines the intensity required to render the stimulus subliminal.

The following table has been compiled from the results of his work in central vision.

<i>Stimulus</i>		<i>Relative Intensity</i>	<i>Value of Light</i>
disc	.95 in. diameter	234	97.4
square	.84 in. x .84 in.	216	139.2
rectangle	1.68 in. x .42	152	495.2
square	.84 in. x .42	154	478.4

The areas of the disc, the square, and the first rectangle are equal, but the rectangle which has the shortest dimension, requires 400 units more of light intensity than does the disc in order to be made just subliminal. The fourth stimulus has half the area of the third, but their shortest dimensions are equal, and accordingly the same amount of light is required to render them both just subliminal. The experiments were extended by Abney to the peripheral retina, and the conclusion was again reached that the shortest dimension of the stimulus and not its area determines the reduction in intensity necessary to render the stimulus just subliminal (p. 183). Since Abney found further that "there is a simple connection [relation] between the intensity of the stimulus color and the extent of the color field," we may infer that he would have us conclude that the extent of the color field is also influenced by the shortest dimension of the stimulus.

The present status of this point may be summarized as follows:

¹⁵ Abney W. de W. *The Sensitiveness of the Retina to Light and Colour*. Philos. Trans., 1897, CXC, Ser. A, pp. 169-171.

Within a certain range of dimensions and particularly for certain regions of the retina, the size of the stimulus is an important factor in determining the extent of the color zones. And with regard to size, the shortest dimension of the stimulus and not its area is, according to Abney, the determining factor. Care must be taken, therefore, to measure accurately the size of the stimulus used in peripheral investigation, also its distance from the observer, and to keep these measurements uniform throughout the investigation.

2. *Intensity and Brightness or White-Value of the Stimulus.*

(a) *The confusion that has arisen with regard to the meaning of intensity and of brightness, and its effect upon the development of methods of working.*

Before we attempt to discuss the influence of the intensity and the brightness of the stimulus upon the limits of color sensitivity, some attention should be given to a definition of terms. The need for this will be shown by a brief examination of the literature on these subjects. A great deal of confusion as to terminology seems to exist, and not a little misinterpretation of fact seems traceable to this confusion. The greater part of the confusion arises from the use of the word *intensity*. This term has been employed at various times to indicate (a) the energy of a beam of spectral light homogeneous as to color; (b) the white-value of a color; (c) the saturation of a color; and (d) the energy of light-waves reflected from a pigment surface as conditioned by the general illumination of the visual field. This equivocal use of the term has now and then apparently led to a wrong interpretation of results, and this in turn to the modification of experimental technique. An example of this is found in the work done by Baird in the Cornell laboratory on "*The Color Sensitivity of the Peripheral Retina.*"¹⁶ In his review of the literature, Baird finds data that lead him to assume that an equation of the white-values of the stimuli employed is essential for a determination of the relative extent of the retina's sensitivity to the different colors. Apparently these data are derived

¹⁶ Baird, J. W. *The Color Sensitivity of the Peripheral Retina*. Carnegie Institution of Washington, 1905.

mainly from three sources: (a) from a study of the color sensitivity of the peripheral retina made by Aubert; (b) from a study by Abney of the effect of changes in the energy or intensity of spectral light upon sensation; and (c) from a study of the limits of color sensitivity made by Landolt.¹⁷ An examination of the investigations made by these men shows, however, that Baird's conclusion is apparently based upon a loose construction put upon the meaning of certain terms. The most striking example of this, as we shall see, results from the interpretation given by Baird to the term *intensity*. Baird uses *intensity* to indicate *luminosity* and, as we shall show, he also uses *luminosity* interchangeably with *brightness* or *white-value*. Landolt and Abney, on the other hand, from the results of whose investigations of the effect of intensity on color sensitivity Baird largely draws his conclusions as to the need of equating the white-value of his stimuli, clearly use the term *intensity* to mean the *energy* of the light-waves coming to the eye.

According to Baird, the first mention of the need to equate in brightness was made by Aubert. Baird writes: "His [Aubert's] results may be summarized as follows:

"1. The brightness of the background has a most pronounced influence upon the extension both of the color sensitivity and of the brightness sensitivity.

"2. The extension of the color zones increases with increase of area of stimulus.

"3. The color sensitivity decreases at very different rates upon different retinal meridians.

¹⁷ Baird claims to derive authority also from the work of Raehlmann, Klug, Chodin, Bull, Hess, and Hegg. We have considered that this authority is derived mainly from Aubert, Landolt, and Abney, however, because Baird discusses the results of these three men and to some extent their methods of working, giving several sentences to show that their work points out the need for equation of the white-values of the stimuli employed to investigate color limits. To the other men from whom he claims to derive authority, Baird devotes merely a sentence to each which states, in case of Raehlmann and Klug, that they had found that the color limits vary with changing brightness of stimulus; in case of Chodin, that he believed that brightness equation was necessary; in case of Bull, Hess, and Hegg, that they had equated the white-values of their stimuli. The discussion of these cases will be taken up later in the paper (see pp. 51-53).

"4. The transitions of color tone are as follows: Red passes through reddish-yellow and yellowish-gray to gray; green becomes yellowish, while yellow and blue undergo no change of tone, but decrease in saturation and finally appear gray.

"5. The relative extension of the color zones can not be determined with any degree of accuracy. Since the width of the color zone is a function of the luminosity of the stimulus, the color-stimuli employed in the determination of comparative retinal limits must all be equated in brightness.

"6. There is a close analogy between the functioning of the central and peripheral parts of the retina."¹⁸

Baird seems to derive his authority for the need to equate in brightness, so far as Aubert is concerned, from the fifth of these points of summary. From the wording of the text it is impossible to state the exact source of Baird's quotation since he bears himself out in his summary only by a general reference to a long list of Aubert's articles on vision.

But the organization of this summary is so closely akin to that given in the *Physiologische Optik*,—the only difference being in the omission by Baird of the third item in the *Optik* summary,—that one seems justified in asserting that this work contains the source of the statement quoted above. In no other of Aubert's articles are all of the points mentioned by Baird touched upon. The earlier articles are narrower in scope than the *Optik* and treat of fewer factors.

Aubert's statement of results in the *Physiologische Optik* is as follows: "Durch meine Versuche wurde festgestellt

"1. der grosse Einfluss welchen die Umgebung der Pigmente auf die Farbenempfindung auch beim indirecten Sehen hat.

"2. der Umstand, dass die Grösse des farbigen Objectes massgebend ist für die Entfernung vom Centrum, in welcher es noch farbig empfunden wird.

"3. dass Pigmente verschiedener Farbtöne unter sonst gleichen Umständen verschiedene Grenzzonen für die Erkennbarkeit der Farbe zeigen.

"4. dass in die verschiedenen Meridianen der Netzhaut die

¹⁸ Baird, J. op. cit., pp. 12-13.

Grenzzonen für die Farben sehr verschieden weit von dem Fixationspunkte liegen.

"5. Schon Purkinje hat verschiedene Uebergänge durch Farbtöne und Farbennuancen beobachtet, und zwar geht auf schwarzem Grunde nach Aubert: Roth durch Rothgelb und Gelbgrau zu Grau, Blau durch immer weisslichere Nuancen zu Grau, Grün durch Graugelb zu Grau, Gelb durch Graugelb zu Grau.

"6. Donders und Landolt haben nachgewiesen, dass die Farbenempfindung auf den peripherischen Netzhautzonen eine dem Centrum gleiche bleibt, wenn die Intensität der Beleuchtung gesteigert wird: also auch beim indirecten Sehen sind Gesichtswinkel und Helligkeit massgebend für die Farbenperception.

"7. dass die peripherischen Theile der Netzhaut für die Farbenempfindung viel schneller ermüden, also die centralen."¹⁹

To Baird's fifth point of summary, the closest approximation that the writer is able to find anywhere in Aubert's works is the sixth conclusion quoted above from the *Optik*. This is: "Donders and Landolt haben nachgewiesen, dass die Farbenempfindung auf die peripherischen Netzhautzonen eine dem Centrum gleiche bleibt, wenn die Intensität der Beleuchtung gesteigert wird: also auch beim indirecten Sehen sind Gesichtswinkel und *Helligkeit massgebend für die Farbenperception*. Nagel bestätigt Landolt's Angabe."²⁰ The question here is whether *Helligkeit* in the above quotation means *brightness of stimulus* which, if our assumption with regard to the source of his authority is correct, Baird has apparently interpreted it to mean. The following points may be cited to show that such an interpretation is very strongly open to question. (a) Aubert himself does not use *Helligkeit* in connection with a qualifying phrase, for example, *Helligkeit der Farben* or its equivalent, while so far as the writer is able to determine, he never uses *Helligkeit* as referring to the *brightness of color* without the qualifying phrase. For example, in his *Physiologische Optik* p. 527 he uses *Helligkeit der Farben*; p. 528, *Helligkeiten der verschiedenen Abtheilungen des Spectrums*; p. 529, *Helligkeiten der Farbtöne des Sonnenspectrums*;

¹⁹ Aubert, H. *Physiologische Optik*, Leipzig, 1876, pp. 541-545.

²⁰ Aubert, H. *Physiologische Optik*, Leipzig, 1876, p. 545.

same page, Helligkeiten der Farben; p. 530, Helligkeiten der Abtheilungen des Spectrums. In his Physiologie der Netzhaut p. 109 he uses, Helligkeit der Pigmente. The same expression is used again on pp. 111 and 112. (b) When using *Helligkeit* without a qualifying phrase, Aubert commonly refers to the *intensity* or *brightness of the general illumination*. For examples of this usage, see Physiologie der Netzhaut, pp. 109, 110, 124; Physiologische Optik, p. 532, and other places. (c) No evidence can be obtained from Landolt from whom the citation is made that brightness of color is referred to. In fact the evidence is strongly against this interpretation. As will be shown in detail (pp. 24-25), Landolt worked with colors of varying energy. He used as stimuli very intense spectral light and pigment papers. The energy of the former was varied directly, of the latter by changing the general illumination which altered the amount of colored light reflected to the eye. In the general statement of his problem Landolt is not concerned with the effect of the brightness of his colors; nor are his results couched in terms of the effect of the brightness of colors. His sole interest was to find the effect on sensation of using colors of great energy or intensity. In the above quotation from Aubert, then, we may conclude that it is strongly open to question whether *Helligkeit* is not also used here in the sense in which we have shown that Aubert most frequently uses the term: the brightness of the general illumination (see (b) above). If so, what he really does claim in this statement, therefore, is that when one is working with pigment colors, the degree or brightness of the general illumination with all of its influences, namely, its effect on the intensity of color, on the brightness of color, on the brightness of the surrounding field, the preëxposure, etc., is one of the factors that determine the extent of the color field; not simply one of these influences, the brightness of color, as he is interpreted to claim by Baird.²¹ Moreover, the writer is compelled to say that in a careful reading of all the articles by Aubert contained

²¹ For Aubert's own statement of his opinion on the question of the influence upon color sensitivity exerted by the brightness of the stimulus see this article, pp. 40-44.

in the long list to which Baird refers, she is unable to find a single statement that would justify the conclusion that Baird has drawn in his fifth point of summary.

Towards Landolt and Abney, Baird takes a slightly different attitude. He does not hold that they have mentioned a need to equate in brightness. In their results, however, he finds justification for equating the white-values of his own stimuli from the construction he puts upon their use of the words *luminosity* and *intensity*. Abney,²² a physicist, had defined *luminosity* as equivalent to *intensity*. In his experiments he had increased or diminished the luminosity or, as he also says, the intensity of a beam of light by interposing in its path a wedge graduated in thickness. The wedge was made of gelatine in which were scattered black opaque particles. The energy of the beam of light was diminished by amounts depending on the thickness of that part of the wedge through which it was made to pass. This "obstruction method" resulted not only in a decrease of the energy of the light, but in a darkening of the stimulus. But Abney was not at all concerned with the effect of the lightness or darkness aspect of the stimulus:—in other words, with the relative inhibitive action of white and black and its influence on the limits of color sensitivity. His purpose was to vary the energy of the light-waves coming to the eye by "obstructing" them by known amounts, and to ascertain the effect of this change upon the color limits. It is true that the lightness or darkness of the sensation quality was altered incidentally, but he apparently had no thought of saying that this was in any sense responsible for the effect obtained, nor is it a necessary inference from his work. Hence Baird is not justified in stating (p. 31) that Abney makes the brightness of the stimulus a factor in determining the color limit, if we take our clue as to what Baird means by brightness from the following passage. "No determination of the relative extensions of the various color zones can ever yield comparative results unless it be accomplished by means of stimuli of equal brightness, or, more correctly speaking, of equal white-value" (see p. 37). For Abney assuredly, does not mean by *lum-*

²² Abney, W. op. cit., 155-195.

inosity what Baird calls *brightness* or *white-value*. Baird falls into a similar error in his treatment of Landolt's results. He says: "An important feature of Landolt's paper is his insistence that no investigation of color vision is complete unless it takes into account the relative luminosity of the stimuli employed" (p. 17). Now when we read in a footnote (see Baird p. 34) that "Under brightness [of stimulus] is included both absolute and relative luminosity of stimulus, *i.e.*, its own brightness and its brightness contrast with its background," we see that the relative luminosity referred to by Landolt means for Baird relative brightness or white-value, and that the work of Landolt is brought forward as evidence for the necessity of equating the white values of the stimuli. Now Landolt worked with both spectral and pigment stimuli. In case of the first, his method was to increase the energy of spectral light; and in case of the second, to increase the amount of light coming to the eye from a pigment surface by increasing the general illumination of the room. Here, as in the case of Abney, we have a change in the amount or energy of the colored light coming to the eye, and incidentally a change in the white-value of the sensation aroused. No separation is made, however, of the two factors: (*a*) the altered energy of the colored light, and (*b*) the change in the white-value of the sensation aroused. Yet Baird finds reason to conclude from Landolt's results that the white-value of the color influences the limits of sensitivity. It is obvious that Landolt's results do not show this at all. All that they do show is that when the amount of colored light given to the eye is increased or decreased, the extent of the zones of sensitivity is altered.²³

Whether or not the white-value of the stimulus can be considered to any degree responsible for changes in the color limits

²³ These three cases taken from Baird's discussion of the work of Aubert, Abney, and Landolt are examples of the cases referred to earlier in the chapter in which a confusion as to terminology has led to a wrong interpretation of results which in turn has been the cause of changes in technique. Baird was led by this confusion, in part intrinsic and in part due to his own misinterpretations, to think that these three men considered that the white-value of the colored stimulus affects the extent of the retina's sensitivity to it, and was influenced thereby to equate the white-values of his stimuli without further investigation.

will be considered by the writer in the experimental section of this paper. What we wish to point out here is that without the isolation and the separate investigation of this factor, Baird concludes from the work of previous investigators in which intensity or energy changes have been made in the stimulus, that the white-value of the stimulus influences the boundaries of the color zones and that, therefore, stimuli should be equated in white-value in all work on the limits of color sensitivity. He says: "It has been established in hosts of instances²⁴ that change of luminosity is, within limits, invariably attended by a corresponding change in the extension of the retinal zone within which the color of the stimulus is recognized. Its significance for the problem is self-evident. No determination of the relative extension of the various color zones can ever yield really comparative results unless it be accomplished by means of stimuli of equal brightness, or, speaking more correctly, of equal white-value" (p. 37). While we grant the significance of changes of luminosity or intensity in the sense in which Abney and Landolt use the terms, we do not admit that this aspect of the stimulus can be standardized in terms of white-value; nor do we grant that any definite evidence whatsoever can be gathered from the results we have quoted above, to show that changes in the white-value of a stimulus affect the limits of the retina's sensitivity to its color, provided the amount of colored light coming to the eye remains unaltered.

To sum up: (a) The white-value of a stimulus may be varied without altering the amount of colored light coming to the eye. This factor, then, may be isolated and its effect on the limits of sensitivity determined apart from any change in the physical intensity of the stimulus. (b) Unless this separation is made, we have no right to conclude that the white-value of the stimulus affects the limits of sensitivity. Baird, for example, drew this conclusion from work in which the separation was not made. (c) The confusion that exists with regard to color terminology

²⁴Beside the three instances mentioned here, Baird cites in support of his position the work of Raehlmann, Chodin, Klug, Bull, Hess, and Hegg. How far their work can justly be cited in support of his position will be shown on pp. 51-53.

has been, we believe, in no small measure responsible for Baird's conclusion.

The terminology which we propose to use in this report may be outlined as follows: *Intensity of stimulus* will be used to indicate the energy of light-waves coming to the eye. *Intensity of sensation*, or *apparent intensity*, will be used as its correlative subjective term. So used, it will signify merely energy or voluminousness of sensation and will have no reference whatever to the white-value of a color. *Saturation of the stimulus* will be used to indicate the proportion of colored to colorless light coming to the eye. *Saturation of color* or *saturation of the sensation* will be used as its correlative term and will refer to the proportion of chromatic to achromatic quality in the sensation. The achromatic sensations will be designated by the terms *white*, *black*, and *gray*; and the terms *brightness* and *white-value* will be used interchangeably to indicate the lightness or darkness of a color.

(b) *The effect of intensity of stimulus.*

A dependence of color sensation upon the intensity of the stimulus has been recognized since the observations of Purkinje. Purkinje noted also that a color stimulus gave a less intense sensation in the peripheral retina than in the central retina. Since that time, it has been claimed (a) that with stimuli of minimal intensity, no color sensation is aroused; (b) that the light-waves arousing the different monochromatic sensations must be of different intensities to give liminal color sensations; that is, the eye is not equally sensitive to waves of different lengths; (c) that, progressively, greater intensity of stimulus is required to give sensation as the stimulus is moved from the fovea to the periphery; (d) that the extent of the color fields is determined within certain limits by the intensity of the stimulus.

The influence of changes in the intensity of the stimulus upon the sensation of color has been investigated by three methods: (1) by determining the effect upon the limens of sensitivity; (2) by determining the effect upon the j.n.d. of sensitivity; (3) by determining the effect upon the limits of sensitivity.

The effect upon the limens of sensitivity. When working by this method, the investigator started with a stimulus that was

below the threshold of sensitivity, and increased its intensity until the sensation of color was just noticeable. This increase in intensity was accomplished in three ways: (a) by increasing the illumination of a pigment surface, and consequently the amount of colored light reflected to the eye; (b) by increasing the intensity of the light used to give a spectrum; (c) by increasing the proportion of color in a mixture of colored and gray pigment stimuli.

The first method of increasing the intensity of the stimulus was used in central vision by Purkinje²⁵ and Aubert.²⁶ Purkinje observed a representation of the spectrum in pigment colors while daylight advanced. He found that blue was the first color to be seen in its true color tone, green next, yellow next, and red last. He made no measurements, however, of the amount of light required to give a just noticeable sensation. Aubert illuminated a pigment surface 10 mm. square by daylight admitted into a dark-room through an adjustable opening in a window. He found that with an opening $\frac{1}{4}$, $\frac{1}{2}$, or 1 cm. square, no sensation of color was obtained. His results are given in the following table.

<i>Opening in window</i>	<i>Stimulus</i>	<i>Sensation</i>
$\frac{1}{4}$ - $\frac{1}{2}$ -1 cm ²	all	no color
$1\frac{1}{4}$ -1 $\frac{1}{2}$	orange	red
2	O,Y,R, rose	O,Y,R, rose
3	blue	blue
3	light green	brown
$3\frac{1}{2}$	light green	light green
5	green	blue
8	green	green

Aubert found that the eye was most sensitive in order to orange, red and yellow, blue, and least sensitive to green.

The second method was used by Raehlmann and Butz. They both used the Bunsen spectroscopic apparatus, which provides for changes in the intensity of the stimulus by means of the Nichol's prism. Raehlmann²⁷ determined the limens of sensitivity to the

²⁵ Purkinje, J. op. cit., 1825, II, p. 109.

²⁶ Aubert, H. Untersuchungen über die Sinnesthätigkeit der Netzhaut. Pogg. Annal., 1862, CXV, pp. 87-116.

²⁷ Raehlmann, E. Ueber Schwellenwerte der verschiedenen Spectralfarben an verschiedenen Stellen der Netzhaut. A. f. O., 1874, XX, pp. 232-254.

different spectral colors at the center of the retina, and at 30° and 60° in the horizontal nasal meridian. He found that the center was most sensitive in order to green, yellow, blue, violet, and red; and the periphery to yellow, blue, green, violet, and red. Butz's²⁸ procedure was as follows: He first determined the liminal value for each of his colors at the center. Starting with this value as unit, he determined how much this value had to be altered to give liminal sensation at 30° and at 60° in the horizontal nasal meridian. He found (a) that the sensitivity to each color increases from 0° to 30° and decreases from 30° to 60° ; (b) that the amount of increase in sensitivity from 0° to 30° and the amount of decrease from 30° to 60° is different for the different colors, that is, the ratio of liminal sensitivity to any two colors is not the same from center to periphery; and (c) that the amount of the increase is greatest, and of the decrease is less in order for violet, yellow, blue, green, and red.

The third method was used by Aubert and Chodin, both of whom employed the Masson disc to find the limen of color sensitivity. Aubert²⁹ found that at the fovea, the eye is more sensitive to orange and yellow than to red and blue. Chodin³⁰ found the sensitivity in the central retina to be greatest in order for orange, yellow, green, and least for blue. In the periphery, he found that the retina is more sensitive to blue and yellow than to red and green.

(2) *The effect upon the j. n. d. of sensitivity.* The effect of intensity upon the j. n. d. of sensitivity has been investigated by Lamansky and Dobrowolsky. Lamansky³¹ used polarized spectral light, and worked in central vision. He found (a) that the j. n. d. of intensity for the different colors increases or, in other words, the sensitivity decreases, as the intensity of the stimulus is

²⁸ Butz, R. Vorläufige Mittheilungen über Untersuchungen der physiologischen Functionen der Peripherie der Netzhaut. Archiv für Anatomie und Physiologie, 1881, pp. 437-445.

²⁹ Aubert, H., Physiologie der Netzhaut. p. 136.

³⁰ Chodin, A. Ueber die Empfindlichkeit für Farben in der Peripherie der Netzhaut. A. f. O., 1877, XXIII, pp. 177-208.

³¹ Lamansky, S. Ueber die Gränzen der Empfindlichkeit des Auges für Spectralfarben. Pogg. Annal., 1871, CXLIII., pp. 633-643.

decreased, and (b) that the j. n. d. of intensity is smallest, or the sensitivity is greatest in order for yellow and green, blue, and red. Dobrowolsky³² in 1876 worked with the colors of the spectrum in central vision and at various points in peripheral vision. Employing standard and comparison fields, he altered the intensity of the comparison by rotating a Nichol's prism before the light-source until its intensity was just noticeably different from that of the standard. Considering that sensitivity varies inversely as the magnitude of the j. n. d., he found (a) that the sensitivity to the different colors decreases with increase of excentricity; and (b) that the comparative sensitivity for the different colors is the same in the center and in the periphery, that is, the order of sensitivity from greatest to least is in each case, blue, green, red. Later in 1881³³ he worked at seventeen different points in the intensity scale. He found again that the j. n. d. for blue is smallest, for green next, and for red largest. In addition he found that the ratio of sensitivity between any two colors as measured by the j. n. d. is not the same for different points in the intensity scale.

In regard to the methods used in the investigations reported above, it may be noted that in no one of the cases have the intensities of the stimuli used been measured and standardized. Tests of the comparative sensitivity of different parts of the retina to the same color and to different colors may be made with propriety by such methods, but not of a given part of the retina to the different colors. Conclusions can not, then, be drawn by the preceding investigators with regard to the comparative sensitivity either of the center or of the periphery of the retina to the different colors. They can, however, show that the center has not the same comparative sensitivity to the different colors that the periphery has. This conclusion may in fact be drawn from the results of all except Dobrowolsky. Dobrowolsky's results alone show that the center and periphery have the same relative sensitivity for all of

³² Dobrowolsky, W. Ueber die Empfindlichkeit des Auges gegen die Lichtintensität der Farben im Centrum und auf der Peripherie der Netzhaut. Pflüger's Archiv., 1876, XII, pp. 441-471.

³³ Dobrowolsky, W. Ueber die Veränderung der Empfindlichkeit des Auges gegen Spectralfarben bei wechselnder Lichtstärke derselben. Pflüger's Archiv., 1881, pp. 189-202.

the colors with which he has worked. A fair test of the comparative sensitivity of the eye to the different colors demands either that stimuli of equal energy be used or that the sensitivity be estimated in terms of units that can be compared. So far as the writer knows, no test of the sensitivity of the retina to color has ever been made with stimuli representing equal amounts of energy. Langley (1889) worked with stimuli of equal energy, but his test was for visual acuity.³⁴ Until stimuli of equal energy are used, it will remain an open question whether or not the retina, either in the center or in the periphery, possesses a different degree of sensitivity to each of the colors.

(3) *The effect upon the limits of sensitivity.* That change in the intensity of the stimulus has an effect upon the limits of sensitivity, has been shown by Abney³⁵ and others. Abney carried on an elaborate series of experiments with spectral light to show the effect of changes of intensity upon the extent of the color fields. He decreased the intensity of the stimulus by placing before it a gelatine wedge in the form of an annulus or ring. This annular wedge was one inch broad. It was graduated in thickness and its transparency was further regulated by black opaque particles which had been mixed with the gelatine in its semi-fluid state. The value of light admitted at O or at the thinnest part of the ring, was 10,000 units;³⁶ that admitted at 360° was 8 units. By interposing the annular wedge in a plane perpendicular to the path of the light and producing the proper amount of rotation, the intensity of the stimulus was reduced by graded amounts. Abney concluded that there is a simple relation between the intensity of the stimulus and the size of the color field.

The extreme position with regard to the effect of intensity upon the extent of the color field is taken by Landolt in the following passage. "In ein absolut dunkles Zimmer fiel nur durch eine kleine Öffnung im Fensterladen directes Sonnenlicht. Dieses wurde auf das äusserste Ende des Perimeterbogens gelenkt. Während wir unser Auge ins Centrum des Bogens setzen, bracht man in die

³⁴ For discussion of Langley's work, see this paper p. 71.

³⁵ Abney, W. op. cit., pp. 155-195.

³⁶ No statement of the value of these units is made by Abney.

kleine, intensive beleuchtete Stelle farbige Papiere von möglicher Intensität der Färbung. Nun bewegt sich das Auge langsam vom entgegengesetzten Ende des Bogens nach Scheitelpunkte zu und es zeigte sich dabei, dass wenigstens mit der innern Netzhautpartie alle Farben schon bei 90° erkannt wurden. Die Grösse des Objectes betrug weniger als 1 cm^2 .

“Als dieselben Prüfungen auch mit Spectralfarben zu machen, entwarfen wir ein Sonnenspectrum im sonst dunkeln Zimmer und liessen es durch eine achromatische Linse auf einen Ende des Perimeters befindlichen Schirm fallen. Dieser hatte eine verändliche Spalte, mittelst welcher man die einzelnen Farben aus dem Spectrum isolieren konnte. Während wir nun wiederum nach langer Adaptation, und bei verbundenem zweiten Auge das eine Ende des Bogens fixierten, würde von einem Assistenten irgendeine Farbe des Spectrums auf die Spalte gelenkt, und wir drehten nun, unter steheter Fixation unserer Fingerspitze, welche sich auf dem Bogen bewegte, das Auge allmählig der Farbe entgegen. Es zeigte sich auch hier wiederum dass alle Farbe schon bei 90° erkannt werden, wenn sie intensiv genug sind.”³⁷

The first to recognize the need for making any sort of intensity equation of the stimuli used to investigate the relative sensitivity of the retina to the different colors was Ole Bull.³⁸ His purpose was to find an accurate method for investigating and measuring the sensitivity of the retina to the different colors. The first essential condition of the method, he considered, must be to equate the colors in saturation and brightness. Briefly, his method of equating in saturation consisted of using complementary colors of such relative intensity that they cancelled each other in a 1:1

³⁷ Landolt und Snellen. *Ophthalmometrologie*. Handbuch der ges. Augenheilk. von Graefe und Saemische, 1874, III., p. 70. The above quotation is given in full in the original in order to confirm (a) the statement made p. 16 concerning the interpretation of Aubert's statement of Landolt's results, and (b) the writer's interpretation, as opposed to Baird's, of Landolt's results, stated p. 18.

A brief summary of the above work is given by Landolt in *Klinische Monatsblätter für Augenheilkunde*, 1873, XI., pp. 376-377; and in *Annales d'Oculistique*, 1874, LXXI., pp.44-46.

³⁸ Bull, O. *Studien über Lichtsinn und Farbensinn*. A. f. O. 1881, XXVII, pp. 54-154.

ratio; that is, he used colors whose color-cancelling or color-quenching power was equal. It will be shown later in the paper (pp. 63-69), that this method is an anomaly, and, so far as the writer knows, is not justified in any investigation of color sensitivity that has yet been proposed. It certainly does not warrant conclusions concerning the relative limits of color nor the relative sensitivity of the retina to the different colors. Using this method of equating Bull concludes, however, that the retina, central and peripheral, is most sensitive to blue, then to yellow, then to red and green.

The second to recognize this essential condition was Hess³⁹ who made an exhaustive "Prüfung des Farbensinnes auf der peripherischen Netzhaut." Hess's object was primarily to furnish Hering with experimental evidence that would enable him to refute the Young-Helmholtz theory as modified by Fick to explain color-blindness. Young's view that congenital color-blindness is due to the absence of one of the three kinds of nerve fibres conceived by him to exist in the retina was adopted by Maxwell and Helmholtz, and extended by the latter⁴⁰ to explain the so-called peripheral color-blindness of the normal eye. Helmholtz believed that the peripheral retina is red-blind, and that this fact could be explained by assuming the absence of the red-sensing fibre. In 1873 Fick⁴¹ and Leber⁴² independently pointed out that this explanation of the peripheral color-blindness is inconsistent with the fundamental assumptions of the Young-Helmholtz theory. Fick declared that according to this theory the sensation of white can be aroused only by the stimulation of all three fibres in equal amounts, or to express it in another way, in balanced proportions. Now, if one fibre were inactive in the

³⁹ Hess, C. Ueber den Farbensinn bei indirectem Sehen. A. f. O., 1889, XXXV, pp. 1-62.

⁴⁰ Helmholtz, H. Handbuch der physiologischen Optik. 1st ed., 1867, pp. 301, 845.

⁴¹ Fick, A. Zur Theorie der Farbenblindheit. Arbeiten aus dem physiol. Laborat. der Würzburger Hochschule, pp. 213-217.

⁴² Leber, T. Ueber die Theorie der Farbenblindheit und über die Art und Weise, wie gewisse, der Untersuchung von Farbenblinden entnommene Einwände gegen die Young-Helmholtz'sche Theorie auch mit derselben vereinigen lassen. Klin. Monatsblätter f. Augenheilk., 1873, XI, pp. 467-473.

peripheral retina, the sensation of white could never be produced in that part of the retina; but instead, the sensation proper to the combined action of the other two fibres would be aroused by white light. If, for example, in the middle region of the retina, the red-sensing fibre, and in the more peripheral regions both the red- and the green-sensing fibres were lacking, the sensation produced by white light in the former case would be blue-green, in the latter blue.⁴³ Further, if one or more fibres were absent in the outer zones of the retina, all the color sensations in these regions would be more saturated than those in the more central regions. For when all three fibres are present, as in the central retina, red, green, or violet light, for example, will stimulate not only its own proper fibre strongly, but will also stimulate the other two weakly. A certain amount of this total stimulation will be in the proportion to give the sensation of white, or more properly speaking, the sensation of gray, and the effect of this colorless component will be to reduce the saturation of the color sensation aroused. If, then, in the peripheral retina only one or two fibres are present, the colorless component will not be present to reduce the saturation of the color sensation, hence, other things being equal, the sensation of color should be more saturated here than that given in the central retina. Fick proposed the following modification of the theory to account for the color phenomena of the peripheral retina. He assumed that from the middle toward the periphery of the retina the relative excitability of the three nerve fibres to lights of the various wave-lengths constantly alters in such a way that at a certain distance from the fovea, namely, in the zone called by Helmholtz red-blind, the red-sensing fibres possess the same excitability as the green-sensing fibres toward lights of all wave-lengths;

⁴³ While in the opinion of the writer, Fick is correct in saying that white could not be produced in the extreme periphery by the action of two of the retinal fibres he is not right in saying what would be produced. For by a literal interpretation of the curves of excitation drawn by Helmholtz to represent his theory, none of the color experiences can be produced by the action of two fibres, excepting those in a small region of the spectrum in the violet. All other color experiences are produced by the combined excitation of all three fibres in some proportion.

and that further toward the extreme periphery, all difference between the relative excitability of the three fibres diminishes and finally 'disappears. In the red-blind zone, then, the intensity-curves for the red- and green-sensing fibres coincide, and in the totally color-blind zone, the curves for all three coincide. Curves drawn in accord with these assumptions will, it is contended by Fick, explain the types of color-blindness found in the peripheral retina without violating any of the fundamental principles of the Young-Helmholtz theory. Helmholtz accepts the essential points of this modification and incorporates them in his theory in his later edition of the *Physiologische Optik*.⁴⁴

In order to disprove Fick's assumption that the relative intensity of response of the three fibres varies from center to periphery of the retina, and thus discredit the Helmholtz theory, Hess advanced three lines of argument. These arguments are as follows. In the first place he claims that there are three colors of the spectrum, a yellow, a green, and a blue, and a mixed color, a bluish-red, which are all invariable in tone from the center to the periphery of the retina.⁴⁵ In the second place, he shows that the proportions in which the complementary colors combine to produce white do not change for the different parts of the extramacular retina. And in the third place he attempts to show that a constant ratio of sensitivity to the members of each pair of complementary colors obtains throughout the retina. In order to make his third point he attempted to obtain red and green stimuli such that the red *Valenz* of the one, or, as he defines *Valenz*, its capacity to arouse red sensation,⁴⁶ should equal the

⁴⁴ Helmholtz, H. *Handbuch der Physiologischen Optik*. 2nd ed., 1896, p. 373.

⁴⁵ For a refutation of this point see footnote, p. 85.

⁴⁶ Hess defines the *Valenz* of his stimuli as their power to arouse color sensation. The writer would question this use of the term. According to its accepted chemical usage, the term might be applied with some degree of propriety to the power which, in terms of the Hering theory, a color possesses to combine with or cancel its complementary color, but scarcely to its power to arouse sensation. Hess, we presume, applies this term to the power of a color to arouse sensation because he assumes that this power is the same or at least equivalent to its power to cancel the complementary color. But since, as we shall show later (see p. 65), this assumption is far from correct, we strongly question the propriety of calling the power of a color to arouse sensation its *Valenz*.

green *Valenz* of the other. He describes his method of doing this as follows: "Als das Nächstliegende erscheint es nun, einen roth- und einen grün-wirkenden Pigmente den gleichen Roth- und Grünwerth dann zuzuschreiben wenn dieselben zu gleiche Theilen, z.B. auf dem Kreisel gemischt eine farblose Mischung geben" (p. 39). The same procedure was used in obtaining his blue and yellow stimuli. Using as stimuli, then, a red equal in cancelling power to a green, and a blue to a yellow, he determines the limits of sensitivity to these four colors. He finds that the limits for his red stimulus coincide with the limits for his green, and the limits for his blue with the limits for his yellow. The limits for blue and yellow, however, fall further out from the fovea than they do for red and green. From these results he concludes (*a*) the sensitivity of the retina from center to periphery falls off with the same rapidity for red as for green, and for blue as for yellow: and (*b*) the sensitivity for both red and green falls off more rapidly than for blue and yellow. Among his conclusions one also finds: "Bei den von uns mitgetheilten Untersuchungen ist die Prüfung des Farbensinnes auf der peripheren Netzhaut zum ersten Male mit genauer Berücksichtigung aller jener Bedingungen vorgenommen worden, welche unverlässlich sind wenn die mit verschiedenen Farben gewonnenen Resultate untereinander verglichen werden sollen" (p. 56). These conclusions are open to the following criticisms: (1) His results do not warrant the statement that the sensitivity for red falls off as rapidly as for green, and for blue as for yellow. For this statement is based on the assumption that if in passing from center to periphery, sensitivity ends at the same point on the retina for two stimuli which have equal power to arouse sensation at the center, they must still have equal power to arouse sensation at the periphery, that is, sensitivity has fallen off as rapidly for one as it has for the other. Now in the first place this assumption begins with a fallacy. For his stimuli were not equated in power to arouse sensation but in cancelling power, and, as we shall show later, the power of a color to arouse sensation and its power to cancel its complementary color are not at all equivalent. And in the second place the assumption is itself incorrect,

for, because of the abrupt decrease in sensitivity as the limits are approached, the relative sensitivity to the two colors may have changed greatly and still their limits have coincided. We have found for example that working with colors of normal saturation under good illumination, it takes, varying with the color, a difference of 90° to 120° of color to make a difference of 1° in the limits. Hess should have determined the limens of color at various points from the center to the periphery of the retina, and have found out whether the ratios of the liminal values of his pairs of stimuli were equal at all of these points.⁴⁷ If so, the sensitivity to each member of the pair must have fallen off with equal rapidity from point to point, otherwise a change of ratio would have occurred. This method would have had the following advantages. (a) Account would have been taken of sensitivity at a large number of points from fovea to limits. (b) Much smaller changes in sensitivity would affect the limens than would affect the limits, especially until very near the limits. (c) No equation of stimuli with its attendant disadvantages would have been needed as long as the liminal values for each color were obtained in terms of the same stimulus all the way out. (2) But even if an equation made in terms of cancelling power were the equivalent of an equation made in terms of the power to arouse sensation, he would not have been justified in concluding, so far as his method of working is concerned, that the red-green sense decreases more rapidly than the blue-yellow sense, because this method afforded him no means of equating the intensities of the members of one of the pairs with those of the other pair. (3) Nor is he justified in his claim that he is the first to investigate the color sensitivity of the peripheral retina who has paid due regard to all the conditions which are essential if the results obtained for this sensitivity are to be compared with one another. One scarcely knows where to begin to refute a

⁴³ While in the opinion of the writer, Fick is correct in saying that white just noticeable difference of sensation could have been determined at each of these points in the retina for various points in the intensity scale. An account could thus have been had of the retina's sensitivity to the members of the pairs of colors at as many degrees of intensity of sensation as was desired.

statement so broadly overdrawn as this. The inadequacy of his treatment of the factors: general illumination, brightness of the stimulus, brightness of the surrounding field and preëxposure, is obvious to anyone who knows the effect of these factors. This inadequacy, however, will be noted at various other points in the paper. It will be sufficient at this point to consider only his handling of the factor, intensity, and that only briefly, for it will also be discussed in some detail at another point in the paper. Hess's problem was narrow and happens to furnish one of the very rare cases in which a subjective equation of the intensity of the stimuli used is justified. But his conclusion with regard to his method of handling the intensity factor is broad and specifically refers to all investigations of sensitivity in which results are to be compared. Such a conclusion is most assuredly not justified. In fact one might almost say that the converse of his conclusion is true. In no investigation of the comparative sensitivity of the retina to the different colors where absolute values are wanted is a subjective equation permissible. Such an equation begs the question at the outset. In such an investigation when an equation is needed, it should be made in terms of a common objective unit, for example, the unit of energy, and when an equation is not needed, the sensitivity should be estimated and expressed in terms of this common objective unit, or some other unit in terms of which results can be compared. In no case, so far as the writer is at present able to outline the field, is a subjective equation justified in an investigation of sensitivity except in certain problems relating to existing color theories or assumptions made for systematic purposes. And not even in these problems, so far as the writer is familiar with them, is an equation made in terms of cancelling power justified in an investigation of sensitivity.

Hegg⁴⁸ was the third investigator to attempt intensity equation. He posits three conditions to be fulfilled "*für die Untersuchung des peripheren Farbensinnes.*" (a) The colors must be physiologically pure, that is, each color must be sensed similarly in all parts of the retina sensitive to it. (b) The colors must be

⁴⁸Hegg, E. *Zur Farbenperimetrie.* A.f.O., 1892. XXXVIII., pp. 145-168.

of equal value in regard to brightness. (c) They must be equal in regard to color content (farbigen Gehalt). Concerning the third condition, Hegg writes: "Wenn es sich nun, was von theoretischen und praktischen Gesichtspunkten aus betrachtet von gleich grosser Wichtigkeit ist, darum handelt, die verschiedenen Farbempfindungen mit einander zu vergleichen, die physiologische Erregbarkeit entsprechender Nerven Elemente nach einem gemeinsamen Massstab zu messen, so ist es selbstverständlich unumgänglich nothwendig, mit gleichgemessenen Reizen die Versuche anzustellen und unsere definirbaren, invariablen Farben anzupassen" (pp. 148-149). Hegg's "gleichgemessene Reizen" were obtained according to the method first used by Bull and endorsed by Hess. But this method of equating can not warrant any conclusion concerning the relative limits of peripheral sensitivity to the different colors. Hegg is then not justified in concluding "dass die Grenzen für Roth und Grün zusammenfallen. Die Grenze für Gelb sind durchwegs ca. 1° enger als für Blau, vielleicht wegen der stärkerem Brechung der blauen Strahlen?" (p. 166).

Baird⁴⁹ was the next to use this method of equating. He determined the relative extension of the different color zones, employing as stimuli light transmitted through gelatine filters. Like his predecessors he also concludes beyond what is justified by his method of working. He expresses his results as follows: "The zone of stable red is coextensive with that of stable green; the zone of stable yellow is coextensive with that of stable blue; and the yellow-blue zone is much more widely extended in all directions than is the red-green zone" (p. 61).⁵⁰

⁴⁹ Baird. loc. cit.

⁵⁰ Fernald (Psychol. Rev. Monog., 1909, X, pp. 60-67) as a minor point in her study of the color sensitivity of the peripheral retina, made a hurried investigation in the nasal and temporal meridians of the limits of an Urroth and an Urgrün, an Urgelb and an Urblau that she claimed were of equal saturation. Her method of equating these stimuli was the same as that of Bull, Hess, Hegg, and Baird. The limits of these stimuli were, she states, determined hurriedly, most of the observations being made at intervals of 5° on the peripheral retina; for example, she states that Urgelb and Urblau were both seen at 85° , and not seen at 90° . In spite of the looseness of these determinations, she concludes that "the limits for the Urgrün are practically coextensive with those for the Urroth, and the fields for the

Bull, Hess, Hegg, and Baird all claim, then, that when the investigation is made with stimuli equated in brightness and in terms of cancelling power, the limits for *Urroth* and *Urgrün*, for *Urgelb* and *Urblau* coincide. It may be inferred from their work that they believe that at least one of the reasons for the non-coincidence of limits obtained by previous investigators is that the colors used were not equated in intensity. Evidence, however, can be derived from the work of Kirschmann,⁵¹ 1893, that this can not at least be considered the sole reason. In Kirschmann's case, in fact, it apparently can not be considered as having any influence at all in producing the non-coincidence obtained. Although his pairs of colors were not equated in intensity, it is obvious that the deviations he obtained from coincidence of limits can not be explained as due to differences in intensity between his stimuli. Kirschmann mapped many meridians of the retina for the limits of sensitivity with both spectral and pigment stimuli. The pairs of colors were not equated in intensity. His color maps show that the outline of the field for each color is irregular in the different meridians, and is different from that of any other color. In general the field for blue is wider than that for yellow, but in certain meridians this order is reversed. The red field is generally wider than the green, but in some meridians the green is the same or wider than the red. Further, the difference between the limits of the colors in some meridians is considerably greater than in others. It is evident

Urgelb with those for the *Urblau*" (p. 65). In addition to applying to this work the criticisms passed above concerning the more careful work of Bull, Hegg, and Baird, all of whom drew conclusions similar to Fernald's, one may express surprise that work so sketchy should be considered as warranting any conclusion whatever. Fernald states, however, that differences of 5° in limits are too small to be of any significance (p. 66). She makes this statement apparently because with the varying conditions of illumination under which she worked, 5° seem to be a normal variation in limits. (It may be too that she considers that this gives her warrant for working only at intervals of 5° .) But as will be shown in the experimental section of this paper, a difference of 5° in limits represents a difference in sensitivity sufficient to raise the limen of sensitivity 200° . In more careful work, then, limits which varied 5° would hardly be considered as "practically coextensive."

⁵¹ Kirschmann, A. *Die Farbenempfindung bei indirectem Sehen*. Philos. Studien, 1893, VIII., pp. 562-614.

that irregularities of this kind can not be due to a difference in the intensity of the stimuli employed, for if blue and yellow, for example, have the same limit when equated in intensity, their limits should retain the same general outline when the colors are of unequal intensity, and should differ only in their distance from the fovea. The zone for the more intense color should in every meridian be regularly some degrees wider than that for the less intense. Relative to the issue between Kirschmann and Bull, Hess, Hegg, and Baird, it is interesting to find that Bull, Hess, and Baird, who all claimed to find coincident limits in all parts of the retina for the paired colors obtained results which, when examined in detail, show the same deviations from coincidence as those which Kirschmann found. Baird, for example, determined the limits of the four principal colors in eight meridians, and concludes: "The results show that the zone of stable-red is coextensive with that of stable-green; that the zone of stable-yellow is coextensive with that of stable-blue."⁵² An inspection of his table of results shows however, that this coincidence is extremely rough. In the results for every observer it is found that in some meridians the green field is wider than the red by 1° , 2° , or 3° ; in other meridians, there is coincidence of limits; and in still other meridians, the green field is narrower than the red by 1° , 2° , or 3° . The same thing is true of blue and yellow. In general, but not in every meridian, yellow seems to be wider than blue on the nasal retina, blue wider than yellow on the temporal. Hess's and Bull's results show similar variations which are in some cases of even greater extent. It is evident, however, from their conclusion concerning the coincidence of limits that they regard these variations as insignificant, probably no more than their normal M.V. for the rough conditions under which they worked. But it should be borne in mind that 2° or 3° of difference in limits is not insignificant when conclusions are to be drawn from the results with regard to the relative sensitivity of the peripheral retina to the members of the pairs of complementary colors. Because of the abrupt falling off in sensitivity just before the limit is reached (see p. 117 ff.), a difference of

⁵² Baird, J. op. cit., p. 61.

2° or 3° in the limits represents quite a large difference in sensitivity. For example, according to our results a difference of 2° in limits represents a difference in sensitivity sufficient to raise the limen for yellow 120° , for green 100° , for red 160° , for blue 170° ; and a difference of 3° represents sufficient to raise the limen for yellow 210° , for green 215° , for red 210° , for blue 215° . Obviously the point is too important to be passed over without re-examination by better methods of working. The limits should be re-determined under conditions that do not give so large an M.V. This has been done by the writer with such a control of all the factors that cause variable results that her M.V. from observation to observation is less than 1° . The results obtained show that this difference in limits is real, and not an error due to any inaccuracy in the method of working. In some meridians the limits coincide, in others they diverge. In short, when the zones are outlined by lines connecting the points representing the limits in the different meridians, these lines for the pairs of colors do not coincide, but criss-cross in a very irregular manner. Therefore, on the basis of our own results as well as those of Kirschmann, the inference can not be drawn from the work of the men who have equated their stimuli in terms of cancelling power that coincidence of limits had not been obtained up to that time because stimuli so equated had not been used. Nor can the conclusion be drawn that even if the stimuli had been properly equated, coincidence of limits would have been obtained. In fact the converse of this conclusion can apparently be drawn.⁵³

⁵³ The writer used as stimuli in these experiments the standard yellow, red, green, and blue of the Hering series. She did not use colors stable in tone as Bull, Hess, Hegg, and Baird claimed to use, because an exhaustive study of this question showed her that stability of tone for all meridians of the retina can be obtained for blue alone of the four principal colors. For a further statement in support of this point, see footnote p. 85. In any event, she is unable to see how the fact that the red and green of this series appear yellow in a small region of the peripheral retina could have any effect on the coincidence of limits for red and green, unless the limit for red, for example, is taken as the point at which all sensation of color disappears, regardless of whether this color is red or yellow. (The writer considered in her own experiments that the limit for a color was the point at which the color sensation lost all trace of its original quality.) However, even if the point at which all sensation of color whatever disappeared be

Therefore, the argument based upon it against Fick's modification of the Helmholtz theory to explain the color-blindness of the peripheral retina can also be refuted insofar as the results on the coincidence of limits can be considered as furnishing argument. This argument is, it will be remembered, that the sensitivity of the retina from fovea to periphery falls off as rapidly to one of the members of the pairs of complementary colors as to the other. It should be borne in mind, however, that the results needed in order to make this argument can not be obtained by a determination of the comparative limits of sensitivity alone.

considered the limit, the following consideration shows that the small component of yellow present in the peripheral retina in the sensations aroused by the red and the green of this series could not have caused the criss-crossing of limits any more than a difference in intensity could have caused it. In fact the point in reality reduces to a question of intensity. If, for example, one of the colors were stronger than the other, this color would have relatively more power to arouse this yellow component, than it would if the colors were of equal intensity. That is, the zone through which the yellow component would be sensed would be broader for this color than it would have been had both colors been of the intensity of the weaker color. And relative to the zone in which a yellow component was sensed, it would not be irregularly broader in some meridians for the stronger color and in other meridians for the weaker color, for in regions in which the yellow sense is relatively weak the zone would narrow for both stimuli. In short, while the influence of the yellow component might cause the zone of sensitivity to broaden for one member of the pairs of stimuli as compared with the other member, it could not cause it to become alternately broader and narrower, in other words, to criss-cross. It is just as obvious that difference in brightness can not be offered as an explanation of this criss-crossing, even if difference in brightness could be shown to have an effect on the limits of sensitivity to the pairs of colors in question. But, as we will show in the experimental section, difference in brightness can be considered as having no effect whatever on the limits of sensitivity. Hence on both counts, difference in brightness can be ruled out of consideration. It would seem, then, that we can conclude that the criss-crossing of limits represents a real relation of sensitivity to the members of the pairs of colors in the far periphery of the retina, even before the investigation is made with stimuli properly equated in intensity. Moreover, when we take into account the fact that a difference of 2° to 3° in the limits represents a large difference in sensitivity we have considerable reason for believing that the ratio of the sensitivity to one member of a pair of complementary colors to the sensitivity to the other member is not the same in all parts of the retina. The point will be definitely determined in the near future by the writer by a careful determination of limens from point to point in many meridians of the retina, with stimuli which consist of lights of spectral purity, measured in terms of a common unit of intensity.

Knowledge is needed of the comparative sensitivity all the way out. Moreover, this knowledge must be based on actual determinations at points not widely separated from each other. The limit is only one of the points at which determinations should be made. In fact, it can scarcely be said to sustain any more important relation to the problem than any other point far removed from the fovea. Furthermore, conclusions can not be drawn from work done by the method of limits with regard to the comparative falling off in sensitivity from fovea to periphery unless it has previously been inferred from a comparison of the results at the center with the results at the limits what the comparative sensitivity should be at the points intervening, as was done by Hess. But this is wholly unjustifiable, for if there is one principle above another that the determinations of sensitivity in the peripheral retina bring out, it is that inferences can not be drawn about sensitivity between points at all widely separated. In fact, practically no conclusions of systematic importance can be justified at all from results obtained by the method of limits, although conclusions of great importance to theory have frequently been drawn from such results. The method of limens should be used instead, for by means of it accurate account can be taken of sensitivity at any point that is desired.⁵⁴

A brief survey of our discussion of intensity shows the following facts:

1. The intensity of the stimulus is a factor influencing both the limens and the limits of color sensitivity. It should, therefore, be carefully standardized in all determinations of sensitivity.

2. The conclusions that have been drawn up to this time concerning the comparative sensitivity of the retina to the different colors have not been justified because of the methods of working that were used in the investigations from the results of which they were drawn; for (*a*) either no standardization of the intensity of the stimuli used had been made; or (*b*) this standardization had been made by an improper method. From the results of

⁵⁴ As stated in footnote p. 83, if a more exhaustive study of the point is wanted, the results of the method of limens should be supplemented by a determination of the just noticeable difference in sensation for various points in the intensity scale at each point of the retina investigated.

the work as it was done the following conclusions alone can be drawn: (a) The comparative sensitivity to the different colors is not the same at the center as it is in the periphery of the retina. This conclusion may be drawn from the results of Chodin and Raehlmann and Butz for the limens of sensitivity. And (b) it is not the same for the members of the pairs of complementary colors at all points even in the small region of the peripheral retina that has been examined, namely in the region comprehended by the criss-crossing limits for these colors. This conclusion may be drawn from Kirschmann's results, from our own, also from those of Bull, Hess, and Baird as shown in their tables giving the limits of their stimuli in different meridians.

3. Broader conclusions than this are justified only when the comparative sensitivity of the retina to the different colors is determined with stimuli properly standardized in intensity. As has been briefly pointed out, the comparative limits of sensitivity can be determined only when the intensities of the stimuli used have been standardized in terms of a common objective unit, for example, the unit of energy; and the comparative limens only when the intensities of the stimuli used have been estimated in terms of this common objective unit, or some other unit in terms of which results can be compared.⁵⁵ This point will be discussed more fully later in the paper (see p. 63 ff).

(c) *The effect of brightness of the stimulus.*

There has been very little discussion by previous investigators whether the brightness or white-value of a color affects the retinal limits of sensitivity to that color, and whether this aspect of the stimulus need then be taken into account in determining the relative extent of the color zones. We have already shown that in such work as there has been, the brightness factor has been obscured by and confounded with the intensity factor.

The confusion of the intensity and brightness aspects of color was noted by Langley in an article entitled *Energy and Vision*, *Philos. Mag.*, 1889, XXVII, 5th ser., p. 1. Langley writes: "While it is quite a familiar fact that the luminosity of any spectral ray increases proportionately to the heat in

⁵⁵ It is scarcely needful to point out that the same kind of standardization is required in order to determine the comparative j. n. d's. for the different colors.

this ray, and indeed is but another manifestation of the same energy, I have recently had occasion to notice that there is, on the part of some physicists, a failure to recognize how totally different optical effects may be produced by one and the same amount of energy according to the wave-length in which this energy is exhibited. I should not perhaps have thought it advisable to make this last remark, were it not that there has appeared in a recent number of *Wiedemann's Annalen* a paper by H. F. Weber on "*The Emission of Light*", in which he tacitly makes the assumption that the luminosity of a color is proportionate to the energy which produces it, an assumption which it is surprising to find in a paper of such general merit and interest."

This confusion, insofar as it has not been due to a misinterpretation of terms, seems to have arisen because the usual method of varying the one factor has necessitated an accompanying variation of the other. Further, the fact that when the intensity or energy of spectral light is increased to a maximum, the color is lightened until white is produced,⁵⁶ has been responsible for the view that light colors are more intense than dark colors, and has led to the custom of determining the energy or intensity of colored light by photometric methods. The photometric method can not, however, be used directly for estimating the intensity of colored light for two reasons. (a) Direct radiometric measurements of energy show that the relative values of the colors of the spectrum as determined by the two methods do not at all coincide. The photometric curve, for example, of the spectra of all light sources of normal intensity is highest in the yellow-green and lowest in the blue and red. The radiometric curve of the visible spectrum of sunlight of the same intensity is, on the other hand, according to Langley,⁵⁷ highest in the red near the C line and lowest in the violet; while the radiometric curves of the visible spectra of most of the artificial sources of light, such as the Nernst, tungsten, and arc lights, are highest in the extreme red and lowest in the violet. (b) The relative photometric values of the colors of all spectra differ widely for different intensities of the same light-

"This statement is true only if the original color has maximal saturation. When one increases the intensity of colors whose original intensity is slight, red and yellow become lighter, blue and green darker. These brightness changes are known as the Purkinje phenomenon.

⁵⁷ Langley, *Energy and Vision*. Amer. Journ. of Science, 1888, XXXVI, 3rd Ser., pp. 359-379; also *Philos. Mag.*, 1889, XXVII, 5th Ser., p. 1; and *Invisible Solar and Lunar Spectra*, *Philos. Mag.*, 1888, XXVI., 5th Ser., pp. 505-520.

source. For medium intensities, for example, the curve is highest in the yellow-green and lowest in the blue. But as the intensity is decreased the curve levels, while its maximum height shifts to the green and its minimum to the red. In short, the photometric value of a color is not a constant but a variable function of its intensity. From the above consideration, it is obvious, then, (a) that the photometric method can not be used to estimate the relative intensities of the colors of the spectrum even for a single intensity of light-source unless for each point of the spectrum considered a factor be determined which will transform the photometric into the radiometric value; and (b) that it can not be used over a wide range of intensities of light-source unless this calibration be previously made for each degree of intensity used. Furthermore, the brightness factor is not inseparably bound up with the intensity factor. It can be isolated. When, for example, one uses a constant amount of colored light, spectral or pigment, and mixes with it a constant amount of white, black, or gray, one obtains stimuli which contain an equal amount of colored light but which have different brightnesses. Up to the present this method of isolating the brightness factor to test its influence has been employed only by Hess, and in his work, as we shall see, it has been used very inadequately.

The discussion whether the brightness of the stimulus affects color sensitivity was raised by Aubert. Aubert was unable to reach positive conclusions concerning its influence. He was led to a consideration of the question by the outcome of an investigation planned to determine the influence of visual angle upon the perception of color in central vision. His results showed that the liminal visual angle was different in case of the different colors, and further, that it differed when the colors were viewed upon white and black grounds. In the discussion of these results he writes: "Zum Theil beruhen diese Verschiedenheiten wohl auf einer verschieden starken Affection des Farbensinnes, zum grösseren Theil aber wohl auf Helligkeitsdifferenzen. Wir haben dabei drei Momente zu berücksichtigen, nämlich die Farbennüance, die Farbenintensität, und die Helligkeitsdifferenz oder den Contrast der Pigmente."⁵⁸ These *Momente* Aubert defines as

⁵⁸ Aubert, H. *Physiologie der Netzhaut*. Breslau, 1865, p. 111.

follows: *Farbennüance* is the sensation given when a color is mixed with white, black or gray. A light blue, for example, contains more white and less blue light than a saturated blue.⁵⁹ *Farbenintensität* is defined as "the impression which is dependent on the intensity of colors: in case of spectral colors, on the amplitude of vibration; in case of pigments, on the intensity of the illumination." "Maxwell," he says, "calls this 'shade': one color may be lighter or darker than another."⁶⁰ Whether or not Aubert also uses the term *intensity of color* as synonymous with *white-value* is open to question. There is evidence in his discussion, however, that he uses it synonymously with *brightness*. For example, when discussing *Farbenintensität*⁶¹ he claims that the intensity factor cannot be made standard because it is impossible to determine which of two colors is the brighter, and because the photometric values of the spectral colors is unknown, the results of Melloni, Dove, and Helmholtz on this point differing widely. But whether or not *brightness* means for him also *white-value* depends upon what he thinks is measured by the photometric method. *Helligkeitsdifferenz* is the brightness relation between a color and its background.⁶² The three factors, then, that Aubert believes we have to consider are (a) the amount of colorless light mixed with the color; (b) the intensity or brightness of the color; and (c) its contrast with the background. The first of these factors, he contends, influences color perception. He finds that the more colorless light is mixed with a pigment color, the the greater must be the illumination at which the color can be liminally sensed; in other words, when the pigment surface reflects a small amount of colored light, the intensity of its illumination must be proportionately greater to give liminal sensation.⁶³ The third of these factors he also considers very important. Colors have different limens and limits of visibility on white and on black grounds. Now the brightness of the

⁵⁹ Aubert, H. loc. cit.

⁶⁰ Aubert, H. op. cit., p. 108.

⁶¹ Aubert, H. op. cit., p. 111.

⁶² Aubert, H. op. cit., p. 112.

⁶³ Aubert, H., Untersuchungen über die Sinnesthätigkeit der Netzhaut. Pogg. Ann. d. Physik und Chemie, 1862, CXV, p. 111, 114.

color determines how great the difference is in the two cases. Blue, for example, is very dark. It is in great contrast to the white field and in much less contrast to the black. Its limit in each case is respectively 15° and 36° ,—a difference of 21° . Red is less dark. Its limits with the white field is 16° , with the black 30° ,—a difference of 14° . Green is a lighter color and more nearly of mean brightness between white and black. In this case the difference in its limits with white and black fields is only 4° . Aubert contends “dass die spezifische Farbenwahrnehmung an der Seitentheilen der Netzhaut um so eher in eine blossе Wahrnehmung von Hell und Dunkel übergeht, je stärker dieselbe mit der Umgebung contrastiert.”⁶⁴ This is stated again in the *Physiologie der Netzhaut*: “Contrast und Helligkeit der Farben sind von grossem Einfluss auf die qualitative Farbeempfindung, so wie auf die Grösse der Netzhautparthie, innerhalb welcher die Farben empfunden werden sein.”⁶⁵ In this regard, then, the difference in the brightness of the colors has an effect on color sensitivity only when the brightness of the surrounding field is made the same for all of the colors. But since it need not and should not be made the same for all of the colors in any investigation of sensitivity, unless the purpose of the investigation is to test the effect of surrounding field on the different colors, this case may be ruled out of consideration. The second *Moment*, the intensity or brightness of the colors, Aubert finds himself unable to isolate. He works with pigment stimuli and can not alter the intensity without at the same time changing the proportion of colored to colorless light reflected from his stimuli; or as he calls it, the nuance of the color. That is, in order to change the intensity of the color, he is compelled to change the amount of white, black, or gray mixed with it.⁶⁶ Further, he thinks it is often impossible to determine which of two colors is the brighter.⁶⁷ However, his experiments to determine the relative intensity of illumination necessary for the

⁶⁴ Aubert, H. Ueber die Grenzen der Farbenwahrnehmung auf die seitlichen Theilen der Netzhaut. A. f. O., 1857, III., p. 54.

⁶⁵ Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 122.

⁶⁶ Aubert, H. op. cit., p. 153.

⁶⁷ Aubert, H. op. cit., p. 111.

liminal visibility of the different colors lead him to think that the brightness of color is not in itself a factor. In these experiments he finds that when the colors are arranged in order according to the intensity of illumination necessary for their perception, they are from least to greatest: orange, yellow, red, light blue, light green, blue, green. But when the illumination is decreased so that all the stimuli are seen as grays, they differ in brightness from light to dark in the sequence: yellow, light blue and green, blue, green, orange, red. Since the order differs in the two cases, he concludes that the differences in the perceptibility of the colors can not be due to their difference in brightness. He says: "Vergleicht man diese Ordnung der Farben nach ihrer Helligkeit mit ihrer Reihenfolge hinsichtlich ihrer Erkennbarkeit bei beschränktem Lichtzutritt, so sieht man, dass die Helligkeit der Pigmente nicht die Ursache seyn kann, dass diese oder jenes Farbenquadrat bei einer geringeren Lichtintensität farbig erscheint."⁶⁸ His final conclusion from this discussion of the three *Momente* is that the colors are not equally perceptible; but it can not be determined in how far this depends upon color tone, color intensity, or color nuance.⁶⁹

In clearing the ground by the discussion of these three *Momente*, Aubert, then, finds himself utterly unable to answer the question: Does the brightness difference between two colors affect the sensitivity of the retina to these colors? because he can not isolate the factors involved for investigation. He, however, recognizes the possibility that brightness difference may affect color sensitivity and for this reason is inclined to think that his own may be only a rough determination. He writes: "To obtain a fine estimation, the influence of brightnesses must be eliminated; and pigments of equal intensity and nuance must be observed upon a background of the same brightness as the pigment. But we do not possess such pigments; and since the photometric value of prismatic colors is not known, an exact estimation of the liminal visual angle at which the colors can be sensed seems impracticable."⁷⁰ As will be shown later, Bull

⁶⁸ Aubert, H. Pogg. Ann. d. Physik und Chemie, 1862, CXV, p. 105.

⁶⁹ Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 123.

⁷⁰ Aubert, H. op. cit., p. 112.

and Hegg take this statement as authority to equate colors in brightness for investigations of the peripheral limit of color sensitivity. It is obvious, however, that the statement contains no real authority for the equation of colors to be used even in investigations of color sensitivity in central vision, because Aubert confesses that he is unable to demonstrate whether or not the brightness of a color affects the retina's sensitivity to that color. He has merely expressed a belief that in fine determinations the equation should be made. Baird, as we have seen, also claims Aubert as authority for equation in brightness, but apparently he has not even this much basis upon which to rest his claim, for in Baird's long list of references to Aubert, none is found to the section containing the statement quoted above. This statement occurs in Aubert's discussion of the influence of visual angle on the perception of colors in direct vision (*Physiologie der Netzhaut*, pp. 108-115). Baird's references to the *Physiologie der Netzhaut* are pp. 89-105; 116-124. As has been shown on p. 13, Baird apparently gets his authority from a discussion in which Aubert is clearly concerned not with the white-value of color but with the total effect of changes in the general illumination. Furthermore, so far as the writer has been able to ascertain, Aubert nowhere else gives as much authority for equating in brightness as is contained in the statement selected by Bull and Hegg upon which to base their claim.

Aubert's opinion that the effect of the brightness of a color upon the retina's sensitivity to that color can not be determined was also held by Chodin who was unable to isolate brightness and intensity from each other.

Chodin writes:⁷¹ "Es bleibt nur übrig die Farben bei gleicher Sättigung und bei mittlerer Lichtintensität zu vergleichen, und da sie unter dieser Bedingung von verschiedener Intensität sind (vielleicht sind die idealen Farben von gleicher Helligkeit, wie Hering sich vorstellt aber wir wissen dies nicht und können es nicht wissen) so liegt es sehr nahe anzunehmen, dass diese verschiedene Helligkeit eine constante Eigenschaft der Farbe selbst sei, welche, wenigstens in merklichen Grade, weder vermehrt

⁷¹ Chodin, A. op. cit., p. 178.

noch vermindert werden kann ohne eine Veränderung des Charakters der Farben selbst herbeizuführen." Chodin goes on to point out one of the difficulties of attempting to obtain stimuli of equal brightness. In case of some of the colors, both spectral and pigment, a change of quality or tone takes place, when, in their state of greatest saturation, their brightness is altered. For example, spectral yellow when darkened gives a reddish-yellow or brown appearance, and the yellow of pigment paper, a decided olive-green appearance. Blue, when altered in brightness, appears reddish. These color changes have been recorded by Chodin, Brücke,⁷² Hegg,⁷³ Rood,⁷⁴ and others. They are marked and are particularly troublesome in that the blue and yellow stimuli, which undergo the greatest changes in quality, are the stimuli that must be altered the most in order to be equated in brightness.

Ole Bull⁷⁵ was the first to mention the problem under discussion in its specific relation to the determination of peripheral color limits. He made no direct test of the influence of the brightness of the stimulus upon sensitivity, but quoted as authority for equating his own stimuli Aubert's statement that for fine determinations of color sensitivity brightness differences must be eliminated. Like Aubert, he was unable to show that the brightness of the stimulus constitutes a factor, but unlike Aubert he does not recognize the need for demonstrating this point. He thus equated his stimuli apparently without ever even having realized the need to investigate whether or not this equation should be made.

Hess⁷⁶ seems to have been the only investigator who has made any attempt whatever to determine whether a light and a dark color of equal intensity have the same or different limits of visibility in the peripheral retina. His test was simple and was applied only to one color. Using two stimuli, the one composed

⁷² Brücke. Wiener Berichte, 1865, LI, p. 10.

⁷³ Hegg, E. loc. cit.

⁷⁴ Rood. On the Effects Produced by Mixing White with Colored Light. Phil. Mag., 1880, X., p. 209.

⁷⁵ Bull, O. op. cit., p. 93.

⁷⁶ Hess, C. op. cit., p. 42.

of 180° *Urgün* and 180° white, the other of 180° *Urgrün* and 180° black, he compared their limits in the horizontal temporal meridian. In each case the stimulus was exposed on a background whose brightness was the same as that of the darker stimulus. Hess found the limit of the dark green to be 25° , of the light green 13° . The value of this brief test lies in that it shows a recognition of the need to investigate whether or not the brightness of the stimulus affects the limits of sensitivity, before an attempt is made to equate in brightness. Hess's method of determining the influence of the factor is, however, open to criticism in two regards. In the first place he made no determination of the amount of brightness difference existing between the colors used. He arbitrarily altered the brightness of green 180° in both directions, that is, toward both black and white. He gives no reason for this choice of 180° of variation of the brightness component. He does not tell us, for example, whether it represents as much brightness difference as there exists between his stimuli, or whether it represents more, or less. If it had represented less, the test would not have possessed due rigor. If, on the other hand, it had represented more, the test would not have been fair for two reasons. (a) Brightness mixed with color inhibits color sensation. This inhibitive action is greater the nearer the brightness mixed with the color approaches white, and is less the nearer the brightness approaches black.⁷⁷ It is obvious, then, that the difference between the amounts of the inhibition of the color by the white and that by the black would increase as the amount of the brightness component increases. If, then, in the above test, Hess had mixed with *Urgrün* in turn amounts of white and black that represented a brightness variation greater than the brightness difference that exists between the standard colors, he would have had a greater difference between the amounts of inhibition in the

⁷⁷ As will be shown in the experimental section of this paper, this may be stated as a general law of the action of brightness on all colors for all parts of the retina with the exception of a region within 5° of the limits of sensitivity to red and yellow, as determined with stimuli of normal saturation and intensity. Within this narrow zone the saturation of red and yellow is reduced more, apparently, by black than by white.

color mixed with white and the color mixed with black, and consequently a greater difference between the intensities of the sensations aroused by them, than he would have had, if a brightness change equal to that existing between the standard colors had been used. His results, then, can not be taken as evidence that the proper amount of brightness change necessary to render the standard colors equal in brightness would change the limits of color sensitivity. Much less can they be taken to show that the amount of brightness difference actually existing between the standard colors acting in conjunction with the greater amount of light coming from the standard colors than from his weakened stimuli would affect the limits of sensitivity.

(b) In Hess's experiment, the color stimulus containing 180° *Urgrün* and 180° white, and that containing 180° *Urgrün* and 180° black both possessed less physical intensity than would stimuli in which less brightness variation had been made. That the degree of intensity of the stimulus is a potent factor in the determination of whether or not the difference in brightness between a light and a dark color of equal physical intensity affects the peripheral limit of sensitivity to that color will be shown in the experimental part of this paper (pp. 104 ff). The results of this work, however, may be anticipated briefly at this point. As has been stated, the action of white when mixed with color inhibits the apparent saturation of the color more than black does. The question under consideration is whether the apparent saturation of a dark color is sufficiently greater than that of a light color of equal physical intensity to widen the peripheral limit of sensitivity to the dark color. Now a determination of the limen of sensitivity to color at a number of points from the fovea to the limits of sensitivity to color shows that the sensitivity to a color decreases slowly from the fovea to a point about 5° within the limit of sensitivity to that color as determined with a stimulus of full saturation,—the point varying slightly for the different colors in its distance from the color limit. From this point on toward the limit, the sensitivity falls off very rapidly. A large increase in the limen is present from degree to degree in this region, often as great as 90° per degree of retina traversed. It

is obvious, then, that if the intensity of the colored stimulus is sufficient to cause its limit to fall within this zone of rapid decrease in sensitivity, the difference in saturation between a light color and a dark color of equal physical intensity would not be sufficient to cause a widening of the limits. On the other hand, if a smaller intensity of color were used so that the limit of the color occurred within the retinal region where color sensitivity alters but slightly from point to point, the greater apparent saturation of the dark color would be sufficient to allow the color to be visible at a point where the light color of less apparent saturation though of equal physical intensity is not sensed. Now the limen for the different colors when mixed with white at the point where the rapid decrease in sensitivity to each begins, is as follows: 120° of yellow; 130° of green; 135° of red; and 145° of blue. These values, then, represent the amount of color that would have to be had in the stimulus to which white had been added to make the limits of sensitivity to them fall just at the boundary between the zones of gradual and abrupt decrease in sensitivity. And since black inhibits color less than white, even less color would be required in the stimuli to which black had been added to make the limits fall at this point. For any amount of color greater than these values, the limits would fall within the zone of rapid decrease. One could, then, add white to his stimuli by amounts varying from 0° to 215° - 240° for the different colors, and black in still greater amounts, and still work within the zone of abrupt decrease. And as long as one works within the region of abrupt decrease, the limits for the colors lightened and darkened by the above amounts will coincide. It need hardly be said that 215° - 240° multiplied by two to express the variation in both directions, represents a much greater brightness difference than exists between the standard colors. On the other hand, for any amount less than the above values, the limits would fall in the zone of gradual decrease. Now Hess's stimuli contained less than this amount of color because his *Urgrün* contained only 244° of green and 116° of blue. 180° of this *Urgrün* would, then, contain but 122° of green and 58° of blue. The intensity of this stimulus was, therefore, so small that ac-

according to our results the limits for both component colors would fall in the zone of gradual decrease of sensitivity. In this zone the greater saturation of the color when mixed with black would cause it to be sensed farther out than the color when mixed with an equal amount of white; that is, the limits for the darkened color would fall further from the fovea than the limits for the light color, as Hess found them to do. In this regard, too, then, it may be said that if in Hess's test, a brightness change was made greater than the brightness difference between the standard colors, and consequently a stimulus was used having smaller intensity than it would have had, if the proper brightness change had been made, the test would have been unfair because the degree of intensity of the stimulus is a factor determining whether or not there is a different limit for light and dark colors of equal physical intensities.

While it is sufficient for our point to show in what respects Hess is open to criticism for arbitrarily selecting 180° of brightness variation without making any determination of how much need be made, a word may be added to show that 180° of brightness variation is much more than was needed. For, the table in which Hess⁷⁸ states the values of the stimuli determined by different observers to be equal in cancelling-action and brightness, shows that in no case was a variation of more than 133° made in one direction, that is, toward either white or black. It is often difficult to see just how much variation was made, because in the majority of cases both black and white were added, hence the net variation was less than the value of either. For example, 105° of yellow, 60° of white, and 195° of black were found by one observer to be equal in cancelling action and brightness to 85° of blue, 84° of white, and 191° of black; for another observer, 200° of red, 48° of blue, 66° of black, and 46° of white were equal in cancelling action and brightness to 188° of green, 39° of blue, and 133° of black. But in no case is the variation in one direction more than 133° , or less than 91° . We may conclude, then, that by his choice of 180° of brightness variation by means of which to compare the limits of a light and

⁷⁸ Hess, *op. cit.*, pp. 45-46.

a dark color of equal physical intensity, he has, roughly speaking, made his brightness variation one and one-half times greater and his intensity only four-fifths of what it should have been, judging from the greatest variation he had to make for his brightness equation. Either one of these items: the overestimation of brightness change or the underestimation of intensity is sufficient both to render his test unfair and, moreover, to account for a very considerable difference in the limits for color mixed with white and for the same color mixed with black.

The second point of criticism of Hess's test is in regard to his method of controlling the brightness of the surrounding field and of the preexposure. He did not use the proper conditions of brightness of screen and of preexposure card. He used a screen and a preexposure which were of the same brightness as the dark stimulus, both in the tests with the dark and with the light color. There was, then, a considerable amount of white added to the light stimulus by contrast from the dark background and by after-image from the dark preexposure over and above the white that was added by objective mixing. Thus while he aimed to add equal amounts of white and black to his pairs of stimuli, he really added much more white than black. Now, we have found that white subjectively aroused apparently has as much effect on the color excitation as white objectively aroused. His test was thus again rendered unfair by his lack of proper conditions with regard to the brightness of the surrounding field and of the preexposure. The surrounding field and the preexposure should have been made in each case equal in brightness to the stimulus.

Hess does not appear to have realized the importance either of the brightness of the surrounding field or of preexposure as factors influencing color limits. He generally equalized the brightness relation between stimulus and background because he seemed to think that accuracy of judgment was fostered thereby,—that one can more readily tell when the color has disappeared from a given stimulus when there is no brightness difference between the stimulus and the background to confuse the judgment.⁷⁹ The preexposure he made of the same quality

⁷⁹ See Hess, *op.cit.*, p. 25.

and brightness as the background. No reason was given for this procedure.⁸⁰ Thus in the above test, he overlooked the diminution in the intensity of the sensation aroused by the lighter stimulus due to the contrast from the surrounding field and to the after-image from the preëxposure,—a diminution which is also in itself sufficient to account for quite a large difference in the limits for a light and for a dark stimulus of the slight degree of intensity used by Hess. Hess's results, then, assuredly can not be considered as showing that the brightness difference between the normal colors affects their limits of sensitivity.

Hegg,⁸¹ like Bull, made no test to determine whether the brightness of the stimulus constituted a factor in the determination of color limits. He gives no reason for the attempt he makes to equate in brightness, other than the fact that Aubert and Bull had mentioned the necessity for this procedure.

Baird was the next to state that the stimuli used to investigate the peripheral color sense must be of equal brightness. His reasons for making this statement have already been discussed in part (pp. 12-19) in order to show how the prevailing confusion with regard to terms has led to misinterpretation. To connect this preceding discussion with what is to follow, a few words to résumé will probably be of service here. It will be remembered that like Bull and Hegg, Baird made no attempt to determine whether or not the brightness or white-value of a color exerts an influence on the limits of sensitivity to that color. Unlike Bull and Hegg, however, he claims to be able to derive authority for equating stimuli in white-value from the work of many investigators,—primarily from that of Aubert,⁸² Landolt,⁸³ and Abney,⁸⁴ but also from Raehlmann,⁸⁵ Chodin,⁸⁶ Klug,⁸⁷ Bull,⁸⁸

⁸⁰ See Hess, *c. op. cit.*, p. 44.

⁸¹ Hegg, *E. op. cit.*, p. 146.

⁸² Baird, *J. op. cit.*, p. 12.

⁸³ *ibid.*, p. 16.

⁸⁴ *ibid.*, p. 31.

⁸⁵ *ibid.*, p. 17.

⁸⁶ *ibid.*, p. 20.

⁸⁷ *ibid.*, p. 20.

⁸⁸ *ibid.*, p. 22.

Hess,⁸⁹ and Hegg.⁹⁰ With regard to these sources of authority, it has been shown (a) that Abney and Landolt do not even claim that brightness difference affects the sensitivity of the retina to color, and that Aubert does not in the references given by Baird; (b) that Bull and Hegg equated their stimuli in brightness merely because Aubert had expressed the belief that such procedure is necessary in making fine determinations of color sensitivity, but since Aubert was unable to demonstrate this necessity, their reason for making the equation has no value;⁹¹ and (c) that Hess's test, upon the results of which he bases his conclusion with regard to the need to equate, was both incomplete and wrongly devised. We have yet to show, then, that no authority can be derived by Baird from the work of Raehlmann, Klug, and Chodin. A claim to authority was derived from the work of Raehlmann and Klug by misinterpretations similar to those made in the cases of Landolt and Abney. Raehlmann and Klug both worked with spectral light and sought to find the effect of decreasing the intensity of the colored light upon the limits of sensitivity. Raehlmann⁹² decreased the intensity of his stimuli as follows: Light reflected from a heliostat was passed through a prism and the spectrum from this source was thrown upon a screen, which may be called screen₁, the distance of which from the light-source was kept constant. This screen contained an opening for the transmission of the colored light. The amount of light transmitted could be regulated by the size of this opening, and the quality could be regulated by shifting the position of the opening along the spectrum. The colored light fell upon a second screen, screen₂, so arranged that its distance from screen₁ could be varied. In two ways, then, could diminution of

⁸⁹ Baird, J. op. cit., p. 27.

⁹⁰ *ibid*, p. 29.

⁹¹ As has been shown, pp. 40-44, Baird, as well as Bull and Hegg, might have had some justification in citing Aubert's authority on the question of brightness equation, from the latter's statement that all brightness differences must be eliminated from stimuli used to make fine determinations of color sensitivity. But this statement of Aubert's is not included in the references to Aubert from which Baird drew his authority.

⁹² Raehlmann, E. Ueber Verhältnisse der Farbenempfindung bei indirectem und directem Sehen. A. f. O., 1874, XX., p. 18.

intensity be produced: (a) by decreasing the size of the opening in screen₁, and (b) by increasing the distance between screen₁ and screen₂. Both methods were used by Raehlmann for producing what he terms *die Abnahme der Lichtstärke*. A change in brightness may have been incidentally produced, but this aspect of the stimulus was of no concern to him. He found that a decrease in intensity decreased the zone in which a color was sensed in its characteristic tone; he most assuredly does not claim, however, as Baird says he does that "the color limits were found to vary with changing brightness of stimulus" (see Baird, p. 17) in the sense in which Baird uses brightness, namely, as white-value. Klug⁹³ used a method somewhat similar to Abney's. He weakened a beam of light by interposing respectively one, two, and three thicknesses of ground glass, and found that the color limits were narrowed in each successive case. Thus he also made no attempt to isolate the effect of the brightness of the stimulus, and his work can not be cited as having any bearing on that problem. In Chodin's work, as we have already seen, the advisability of equating in brightness was discussed and decided against because of lack of evidence for the need of equating and because of the changes in color tone produced by changing the brightness of the colors. In giving Chodin as one of his authorities for equating, Baird refers to the passage in Chodin's article quoted in the original in this paper, pp. 44-45.

Baird writes: "Chodin remarks in his introduction: 'It is self-evident that in comparing the retinal sensitivity to different colors, the color stimuli employed must be of equal brightness and of equal saturation.' But this very essential condition was not fulfilled in his own experiments" (see Baird, p. 20). Baird has here again made a misinterpretation. The rather free translation of Chodin's statement: "Es bleibt nur übrig die Farben bei gleicher Sättigung und bei mittlerer Lichtintensität zu vergleichen"⁹⁴ and the failure to read carefully the discussion following it, are responsible, we presume, for the misinterpretation.

It is obvious from the foregoing résumé that the factor, bright-

⁹³ Klug, F. Ueber Farbenempfindung bei indirectem Sehen. A. f. O., 1875, XXI., pp. 274-278.

⁹⁴ Chodin, A. op. cit., p. 178.

ness of the stimulus, has been very inadequately treated in the literature. The specific question has never been answered, in fact has never really been investigated: Does the amount of brightness difference existing between the colors influence their limits of sensitivity in the peripheral retina? Aubert⁹⁵ and Chodin⁹⁶ and others have shown that the sensation limen of color when mixed with white is higher than the limen when mixed with black. This fact may be explained as due to the superior inhibitive power of white. But within what limits this greater inhibitive action of white is sufficient to cause the peripheral limit of a color mixed with white to be narrower than that of an equally intense color mixed with black has not been determined. And certainly it has never been shown that the brightness difference that exists between the standard colors at full saturation exerts an inhibitive action sufficiently strong to cause a change in the peripheral limits. It has never been claimed, for example, that a light color in its state of maximal saturation is more inhibited for sensation than a dark color in its state of maximal saturation by the brightness component inherent in each; in other words, that a saturated yellow is more inhibited by its brightness component than is a saturated blue by its brightness component. In fact, in strange contradiction to this, it has often been held that the colors which have the stronger white component are the more intense. Yellow, for example, has been frequently called a more intense color than blue just because of its proximity to white.

We must conclude, then, that the assumption that color limits must be investigated with stimuli of equal brightness is probably based upon the belief that stimuli differing in brightness differ also in intensity. This belief has doubtless arisen from the fact that as stimuli are ordinarily varied, a change of brightness is accompanied by a change of intensity, and conversely a change of intensity is accompanied by a change of brightness. But brightness and intensity are not inseparable variants. Conclusions should not be drawn, therefore, until the influence of bright-

⁹⁵ Aubert, H. *Physiologische Optik*, p. 532.

⁹⁶ Chodin, A. *op. cit.*, p. 183.

ness change has been investigated in separation from intensity change. Since this investigation has not been made, we are forced to consider that the influence of the brightness of the stimulus upon the limits of color sensitivity is at present an open question, despite the verdict to the contrary by Bull, Hegg, Hess, and Baird. We have, therefore, included it in our own work as one of the points to be investigated. The results of this investigation are reported in the experimental section of this paper.

3. *Brightness of the Field Surrounding the Stimulus.*

The recognition of the influence exerted by the field surrounding the stimulus upon the limits of the color zones, has led to the substitution of the campimeter for the perimeter in investigations of the color sensitivity of the peripheral retina. The campimeter provides a means of readily changing the brightness of the field which surrounds the stimulus, so that the effects of these changes may be studied both upon the limens and limits of color and upon the quality changes that appear as the stimulus is carried from the fovea to the periphery.

The influence of the field surrounding the stimulus is two-fold. In the first place, it directly modifies the stimulus by contrast induction, provided there is brightness opposition. This effect was observed and to some extent investigated by Aubert and Woinow before the campimeter came into use. In the second place, the campimeter screen, when of sufficient size, stimulates the entire retina uniformly and guarantees an equal brightness-adaptation of every portion. It was the recognition by Krüchow⁹⁷ that former methods had allowed the retina to become unequally fatigued to chance objects in the surrounding room, that led directly to the first use of the campimetrical method of working. Krüchow did not, however, study the effect of different backgrounds. He used a uniform gray field to stimulate the surrounding retina, and mounted stimuli on cards of equal quality. In subsequent investigations, a black background was used almost exclusively. So far as induction is concerned,

⁹⁷ Krüchow, loc. cit.

this screen gives conditions with the light-adapted retina somewhat similar to those existing in dark-room work; that is, in each case the stimuli are lightened by contrast from the surrounding dark field.

Woinow and Aubert worked only with small areas of background and thus secured the given brightness stimulation over but a small zone surrounding the part of the retina stimulated to color. Woinow⁹⁸ placed a disc made of black and white sectors behind the stimulus to be investigated. He found that, when the sectors were so adjusted that when rotated they formed a dark gray, the color limits were the same as when the sectors were arranged to give a light gray sensation. From these results, he concludes that the color zones are not influenced by the brightness of the field surrounding the stimulus. Aubert⁹⁹ fastened colored paper stimuli on white and on black cards. He found that the black card gave relatively wider limits for red; and that the white card gave relatively wider limits for yellow, green, and blue, except for very small stimuli.

The first campimeter described was apparently what is now called the Hering color-mixer.¹⁰⁰ Hess¹⁰¹ was the first to employ it for an investigation of peripheral color sensitivity. He and later Tschermak¹⁰² tested by means of it the influence of the brightness of the surrounding field upon the color limits. With this apparatus pigment stimuli are observed through an opening in a large gray screen, placed in the horizontal, which can be turned toward or away from the source of light, and in this way a surrounding field can be obtained that is lighter, darker, or equal in brightness to the stimulus at its point of disappearance as color. Hess and Tschermak both found that the limits of sensitivity to

⁹⁸ Woinow, M. loc. cit.

⁹⁹ Aubert, H. *Physiologische Optik*. pp. 541-543.

¹⁰⁰ Titchener in *Experimental Psychology, Instructor's Manual, Qualitative*, 1901, p. 20, ascribes the description of this apparatus to Hering, giving as reference A.f.O., 1889, XXV., p. 63. The writer is unable to find any mention of this apparatus in this or any other of Hering's articles. It is, however, described in some detail on p. 25 of the paper by Hess which just precedes and accompanies the Hering article to which Titchener refers.

¹⁰¹ Hess, C. loc. cit.

¹⁰² Tschermak, A. op. cit., p. 561.

color were widest when the surrounding field was equal in brightness to the stimulus. If the stimulus appeared lighter or darker than the surrounding field, the limits were narrowed proportionately to the loss of saturation of the stimulus color due to the action upon it of the brightness quality induced by the background.

Fernald¹⁰³ used a vertical campimeter. She summarizes her results with white and black screens as follows: "All the colors except the reds are perceived at a greater angle of eccentricity with the dark than with the light backgrounds."

The only quantitative estimates of the effect of different backgrounds reported by these experimenters is given in terms of the effect upon the color limits. In no case has the amount of white or black induced by a given screen been determined, nor has the effect of the induction upon color sensitivity ever been tested in any part of the retina by the most direct means available, namely, the determination of the limen or threshold of sensation. Neither has any attempt been made to isolate the influence of the background from the influence of the brightness of whatever stimulates the retina immediately before the exposure of the stimulus. This factor, which we shall discuss under the name of *pre-exposure*, is effective through the intensive brightness after-image that is set up on the retina and is superimposed upon the colored stimulus when it is exposed. Its importance has never been recognized by previous investigators, nor has its effect ever been studied in isolation from the effect of the brightness of the background. In short, in surveying the literature, one can scarcely help but feel that the study of the influence of the surrounding field has been neither analytic nor systematic.

4. *The General Illumination.*

The effect of the general illumination of the retina on color sensitivity has been recognized since the time of Purkinje and Aubert. It has been studied in some detail by a number of experimenters, among whom may be mentioned Kramer and Wolffberg. Both have shown that the sensation aroused by the colored stimulus is weakened by a reduction of the general

¹⁰³ Fernald, G. M. The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. Psychol. Rev. Monog., 1909, X, No. 42.

illumination, but neither, it may be mentioned, has given a method of keeping the general illumination constant. Kramer's¹⁰⁴ purpose was to determine the sensitivity of the eye under different intensities of daylight and artificial illumination. His method was as follows. Stimuli, 4 mm. square, of blue, yellow, red, and green paper on a black background were used. The distance at which the stimulus had to be placed from the observer to be just recognized as colored, was tested by sunlight and when the sky was obscured by clouds and for three intensities of each of the following sources of artificial illumination: candle light, gas, petroleum, sodium, potassium, strontium, and calcium lights. His results may be summarized as follows: (1) Red is seen at the greatest distance in all lights except calcium, in which case green is seen when farther away than red. The other colors are recognized in the order green, yellow, blue. (2) All the colors are recognized at a greater distance when seen by sunlight than when illuminated by artificial light or the dull light from a clouded sky. (3) As the intensity of the artificial illumination is decreased, the colors must be placed nearer the eye to be recognized. Kramer's method of working, however, may be criticized because he ignored the white contrast which the black background induced across the stimuli. The induction across the stimuli whose sizes were only 4 mm. square must have been considerable. It was, moreover, of different amounts in each case; because brightness contrast is greatest when there is maximal brightness opposition. The modification of the light colors, as a result of contrast induction, must, therefore, have been greater than that of the dark colors.

Wolffberg's¹⁰⁵ interest was in the influence of gradual alterations of the general illumination on the light and the color sensitivity of the central and of the peripheral retina. His room was illuminated by daylight entering through a window. Fifteen different degrees of illumination were produced by fastening from one to fifteen thicknesses of tissue-paper over the win-

¹⁰⁴ Kramer, J. Untersuchungen über die Abhängigkeit der Farbenempfindung von der Art und dem Grade der Beleuchtung. Inaug. Diss., Marburg, 1882.

¹⁰⁵ Wolffberg. Ueber die Prüfung des Lichtsinnes. A. f. O., 1887, XXXI., pp. 1-78.

dow. The illumination obtained when the window was uncovered was called 15/15; when covered with one thickness of tissue-paper, 14/15, etc. His method of determining the effect of variations of illumination upon the central retina was as follows: Pigment stimuli were placed at a standard distance of 5 meters from the observer, and the size of stimulus necessary to render it just visible in its true color was determined. In the peripheral retina, he investigated to what extent the limits of white and of colored stimuli were altered by reducing the illumination. In all his experiments, the stimuli were fastened on a black background. Wolffberg's results for the central retina are shown in the following table. The stimuli were circular in shape and of diameters given in columns 2, 3, 4, 5, and 6.

Illumination	Size of Red Stimulus	Size of Blue	Size of Green	Size of Yellow	Size of White
15/15	.5 mm.	3 mm.	3 mm.	1.5 mm.	.2 mm.
14/15	1.5	5	4	2	.5
13/15	2	6	6	4	1.
12/15	2.5	12	12	4.5	2
11/15	3	20	20	5	2.5
5/15	10	50	50	10	6

These results show that in the central retina a decrease of illumination has a greater effect upon the sensation of color than upon the sensation of white. Wolffberg next tested the effect of a gradual decrease of illumination upon the limits of sensitivity to white and to the colors. He found that the extent of the visual field was not narrowed for white when the illumination was decreased to 1/15. The color limits, however, narrowed gradually when the illumination was decreased from 15/15 to 3/15. The narrowing was in no case more than 15°. The relative extents of the fields remained unaltered, that is, the order of size was in every case blue, red, and green.

Although special investigations have been conducted by Kramer, Wolffberg and others to show the effect of changes in the general illumination upon color sensitivity, in general little if any precautions have been taken by earlier experimenters to prevent such changes when investigating color sensitivity. Either the experimenter has not considered the influence of the

general illumination, or he has been satisfied to take the rough precaution to work only on bright days at stated hours. Ole Bull,¹⁰⁶ for example, commented at length on the factor of general illumination, but suggested no method for its standardization. He writes: "The amount and nature of the general illumination are of more significance in perimetrical observations than one is accustomed to consider. It must always be noted whether the sky is clear or cloudy, whether it rains or snows. The extreme limits of the visual field for mixed light undergo such wide fluctuations that it is of little value to establish an average limit on the basis of a number of measurements. Changing illumination, conditioned by the time of day and of year during which the work is carried on, as well as the locality in which it is undertaken, produce variations in the same stimulus large enough to cause differences of from 10° to 20° [in the limit of sensitivity]. Especially in the nasal parts of the retina does the illumination influence the color limits, while their position remains more constant in the temporal retina." Fernald,¹⁰⁷ however, did make some attempt to obtain a standard illumination. She arranged white curtains at the windows of her optics-room which could be lowered on bright days and drawn on dark days. This rather crude method was used also by Thompson and Gordon.¹⁰⁸ It is scarcely necessary to point out that the method lacks the first essential of standardization, namely, a means of measuring.

It is surprising that Wolffberg as the logical corollary of his work, did not draw attention to the importance of standardizing the illumination of the visual field in all work on the color sensitivity of the retina, and show how it could be accomplished by a modification of his method of working. He already had at hand one of the essentials for standardizing, namely, a method of changing the illumination of his room. The other essential, a method of measurement by means of which an illumination could be identified with a previous illumination chosen as standard,

¹⁰⁶ Ole Bull. *Perimetrie*. Bonn, 1895, p. 8.

¹⁰⁷ Fernald, G. M. *Psychol. Rev.*, 1905, XII, p. 392.

¹⁰⁸ Thompson and Gordon. *A Study of After-images on the Peripheral Retina*. *Psychol. Rev.*, 1907, XIV, p. 122.

might have been derived from his results. For example, it would seem to have been a simple matter for him to have chosen as standard the particular illumination at which the red stimulus of 2.5 mm. diameter, the blue and green of 12 mm. each, the yellow of 4.5 mm., and the white of 2 mm. were just recognizable at a distance of 5 m. Stimuli of those sizes, it will be seen from the tables, were just recognizable at this distance at the illumination called 12/15, when 15/15 represents the illumination "bei günstige Tagesbeleuchtung." Using this condition as an index of the standard illumination, he could at any time have adjusted the illumination of the room by adding to or subtracting from the layers of tissue-paper covering the window, until the stimuli of these sizes were again just recognizable at the given distance. The accuracy and sensitivity of this method could have been tested by comparing the results of a series of determinations. An accurate and highly sensitive method sustaining some similarity in principle to the method suggested here, will be described by the writer in the experimental part of this paper.

The influence of changes in the intensity of the general illumination upon visual acuity has received some attention from physiologists and oculists. Although their work has no direct bearing on the influence of change of illumination upon color sensitivity, it may be of interest to note briefly their methods of dealing with these changes.

Schweigger¹⁰⁹ in 1876, using the Snellen series of optotypes and the formula $V = \frac{N}{n}$ in which n represents the distance of the test-object from the eye of the observer, and N the number of the series of the smallest of optotype series that can be recognized at that distance, found that on a clear day his visual acuity equalled 20/15, on a cloudy day it equalled 30/15. To correct for the errors in visual acuity introduced by changes in the illumination he first found the number of the series of the smallest optotypes that he himself could read at a given distance, then he determined this value for the patient at the same distance. Using his own results $V = \frac{N}{n}$ as standard, he determined the ratio of the patient's results $V = \frac{N^1}{n}$ to his own. This ratio $\frac{N^1}{N}$, he considers the expression of what the patient's visual acuity would be at standard illumination.

Cohn's and von Hoffman's interests lay mainly in testing the eyes of schoolchildren and in determining what was the lowest intensity of illumination of the schoolroom suitable for work. Cohn¹¹⁰ in 1867 and 1883

¹⁰⁹ Schweigger, E. Sehproben. Berlin, 1876, Preface, pp. III-IV.

¹¹⁰ Cohn, H. Untersuchungen der Augen von 10060 Schulkindern. Leipzig, 1876, p. 101; Hygiene of the Eye in Schools, translated by Turnbull, 1883, p. 131.

claims that as there is no photometer available for the measurement of the intensity of daylight, the eye must be its own photometer. Later in 1892¹¹¹ he states that L. Weber has made a daylight photometer, but as this apparatus is difficult of access, he would recommend apparently that the changes in visual acuity experienced by the eye with changes of illumination be used as a means of identifying a given degree of illumination. He endorses von Hoffman's¹¹² method of accomplishing this. According to this method, Type No. 30 of the Snellen optotypes is placed in the schoolroom 15 feet from the eyes of a child whose visual acuity is 15/15. If the child recognizes the letters of the test, the room is sufficiently well-lighted. Work in the room is to be suspended as soon as the child can no longer recognize the letters of the test. This provided a practical method, not for measuring the illumination of a room, but for detecting when a room has insufficient light for purposes of schoolwork.

Nicati¹¹³ tested the influence of change of the intensity of artificial illumination upon visual acuity. His work was purely quantitative. He proposes a unit of measure by means of which to study this effect. This unit he calls a *photo*. A *photo* is the smallest intensity of light which when placed 1 meter from a test-object printed in black on a white card gives to normal monocular vision a normal acuity. The method of measuring the intensity of an illumination in *photos* is as follows. A source of light is brought towards the test-object until the observer has normal acuity. The intensity of the source then equals as many *photos* as the square of the distance of the light-source from the test-object, measured in meters. Nicati finds that there is an absolute logarithmic relation between visual acuity and intensity of illumination. As visual acuity is decreased in arithmetical series, intensity of illumination decreases in geometrical series. His table showing this relation is as follows:

Visual Acuity	1	.9	.8	.7	.6	.5	.4
Distance of source	1M		2M		4M		8M
Intensity in <i>photos</i> .	1	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{1}{64}$

Since this relation exists, either the intensity of illumination can be considered a measure of visual acuity, or visual acuity can be considered a measure of the intensity of illumination. That is, the scale of visual acuity is a photometric scale and can be used as such. To measure the illumination of a room in *photos*, then, the visual acuity should be determined in different portions of the room, and the average of the *photos* corresponding to these values in the acuity scale be taken as the measure of the illumination of the room in *photos*. The method as formulated is apparently serviceable as a means of estimating the illumination of a room chiefly, if not entirely, when it is below what is needed for normal acuity of vision.

¹¹¹ Cohn, H. Lehrbuch der Hygiene des Auges. Wien und Leipzig, 1892, pp. 34-35.

¹¹² von Hoffman, H. Augenuntersuchungen in vier Wiesbadener Schulen. Klin. Monatsbl. f. Augenheilk., 1873, pp. 289-290.

¹¹³ Nicati, W. Physiologie Oculaire humaine et comparée normale et pathologique. 1909, p. 163ff.

B. METHODS OF STANDARDIZING THESE FACTORS.

1. *Size of the Stimulus.*

No special method of standardizing the size of the stimulus is required. Each experimenter who has recognized it as a factor has chosen what he considered the most favorable area to work with, and has used that area in all of his comparative determinations. No limitations as to area have been prescribed other than that it must not be too large nor too small.

2. *Intensity of the Stimulus.*

As a general introduction to our discussion of the methods that have been used to standardize the influence of intensity, we wish to call attention once more to the fact that in no one of these investigations have the stimuli employed been equated with regard to the energy of the light given to the eye, nor have they been standardized in terms of any fixed unit of intensity that can be compared; and that until this is done, we have no proper means of determining the comparative limits of sensitivity to the different colors; nor of determining and expressing the comparative limen or j. n. d. of sensitivity. For example, attempts to determine the relative sensitivity of the retina to the four principal colors have been made among others by Aubert, Chodin, Raehlmann, Butz, Lamansky, and Dobrowolsky: also by Bull, Hess, Hegg, and Baird. As stated above, however, these experimenters did not equate their stimuli with regard to the energy of light given to the eye for the investigations of the limits of sensitivity nor estimate sensitivity in terms of a common unit for the work on limens and j. n. d.'s of sensitivity. The last four, however, did attempt to equate in intensity, but the equation was made in terms of a subjective measure arbitrarily selected, namely, the proportion in which the pairs of antagonistic colors must be combined to produce gray, or, in terms of the Hering theory, to cancel each other.

At this point, two general criticisms may be passed on this method of equating. (a) The stimuli should not be equated in terms of any subjective measure if one is to test the comparative sensitivity of the retina to the different colors. This begs

the question at the outset. If, for example, a direct judgment of the intensity of the sensations aroused by two stimuli either at the limen or higher in the intensity scale be taken as the criterion for determining their equality, the method begins by making the stimuli of such physical intensity that they are sensed equally. In no fashion could the comparative sensitivity of the retina to the colors in question be determined by such stimuli. Suppose, for example, the limits of sensitivity of the peripheral retina were to be investigated, and for this, the stimuli which had been made subjectively equal for the central retina were used, the results obtained would not at all express the comparative limits for the colors in question. If these limits should be found to coincide, the conclusion could not be drawn either that the sensitivity of the retina to these colors extended only to this point, or that there was equal sensitivity at this point to the colors used. At most no more could be said than that approximately the same ratio of sensitivity to the two colors obtained in this region that was present at the point in the central retina for which they were equated; but this ratio may not be a 1:1 ratio. In fact, the investigator who gets his limits to coincide with stimuli so equated finds himself in the somewhat ludicrous position of having made his conditions such that the limits could not help but coincide, regardless of whether they actually ought to do so or not. He is not working with real limits, but with limits arbitrarily established, and the coincidence he finds is not a fact, at least not so far as he is able to determine by his method of working, but an artifact. To illustrate, the retina might be much more sensitive to red than to green; but if the red stimulus were reduced in physical intensity until the sensation it aroused was equal in intensity to the sensation aroused by the green, it is obvious that the comparative sensitivity to these colors could not be directly tested at any point. The limits of the red zone so determined might, for example, coincide with the limits of the green zone, although the extent of the red zone would have been much wider had stimuli of equal physical intensity been used. So much may be said for this as a type of subjective measure of equality, and what is said in criticism of its use for

investigating the comparative sensitivity of the retina has a general application to all subjective measures.

(b) The stimuli, especially should not be equated in terms of the cancelling power of antagonistic colors.¹¹⁴ This method is anomalous. One scarcely knows what it does accomplish. On the one hand, stimuli so equated are in no way equated in physical intensity; and on the other hand, it would be the merest assumption to say that they have equal power to arouse sensation. To demonstrate this, let us compare certain colors with regard to their comparative power to arouse sensation and to cancel each other. There are three ways by which we may judge the power of a color to arouse sensation:— (a) the value of its limen when mixed with a gray of equal brightness; (b) the value of its j. n. d. at different points in the intensity scale; and (c) the direct or introspective judgment of its intensity. Estimated in all of these ways, spectral red, as prepared in pigment colors by Maxwell after Helmholtz, has greater power to arouse sensation than the green of the series. And yet on the color-mixer, it requires 240° of this red to cancel or obliterate all trace of 120° of the green. And if sufficient blue be added to the mixture to give gray, the proportions of red and green are 165° and 115° respectively. Thus, whether the result of the combination is yellow or gray, the red stimulus, although it has the greater power to arouse sensation, is required to be in considerable excess of the green. We regret that we can not make a similar comparison for the blue and yellow of the Maxwell series, because we were unable to procure them in season for this work. But using the blue and the yellow of the Hering pigment papers, we find that this blue has a lower limen in a gray of its own brightness than the yellow has in a gray of its brightness, and that introspectively it is judged much more saturated than the yellow. And still at the general illumination we have chosen as our standard, 200° of blue are required to cancel 160° of yellow.¹¹⁵

¹¹⁴ There are problems in the optics of color in which subjective equations of intensity may be desired. For a description of what the writer considers a proper method of making the subjective equation, see this paper p. 83, footnote.

¹¹⁵ If the illumination is decreased, we find that a different proportion

In a later paper, we shall show that if the complementary colors can be assumed to cancel each other, because a certain amount of the one when combined with a certain amount of the other, kills it for sensation, then, by the same token, the non-complementary colors may be assumed to exercise a degree of this cancelling action. For a definite and considerable amount of each must be mixed with any other before it is sensed, the amount required varying over a wide range when one of them is combined with each of the others in turn. We may draw upon the non-complementary colors, then, for a further demonstration of our thesis that the cancelling power of colors upon each other is no measure of their power to arouse sensation. A notable instance of this is the combination of red and yellow to give orange. Working with the Hering pigments, we find that the standard orange of the series, judged as sensation, seems to be equally red and yellow. The standard red of the series, however, which is chosen to form the orange, has greater power to arouse sensation than the yellow by all of the tests mentioned above. Still 295° of red are required to be combined with 65° of the yellow to give the orange which as we have said is equally red and yellow as sensation. Orange furnishes us with only one instance of the non-equivalence of cancelling power to sensation-arousing power that may be found among the combinations of non-complementary colors.¹¹⁶

We must, then, conclude that even if one were to err so profoundly as to choose a subjective measure for equating the intensity of his stimuli for an investigation of the comparative is required to produce cancellation. This difference depends upon the fact that colors do not lose their saturation with equal rapidity with decrease of illumination. The dependence of cancelling proportions upon the general illumination may be pointed out as a minor source of error in the use that has been made of this method by investigators who have conducted their experiments in daylight, for they did not work at an invariable or standard illumination.

¹¹⁶ In the above demonstration that cancelling power can not be taken as the equivalent of sensation-arousing power, we have assumed that we have not left our work open to criticism in the use of pigment instead of spectral colors, or even in passing from one series of pigment colors to another, because in each case, our test of the cancelling power and of the sensation-arousing power was made with the same stimuli.

sensitivity of the retina to the different colors, this measure should not be selected in preference to the power to arouse sensation as determined either by limen tests, by direct introspective judgments of intensities, nor by the j. n. d. method described on p. 83 footnote. One can only surmise the following reasons for the selection. (a) The limen and the just noticeable difference tests, either of which is a proper method of estimating the power of a stimulus to arouse sensation, were probably not taken into consideration at all. The alternative test, the introspective judgment of equal intensities, is difficult to make. And the method given on p. 83 footnote, which is preferable to any method known to the writer for subjectively equating stimuli of all degrees of intensity, has never been suggested even in principle prior to the publication of this paper. It may have been thought that equality based on cancelling power could be substituted for the equality as determined by the other methods.

The reason for selection of equation in terms of cancelling power is not stated by any one of the four men who has made this selection. Considering the statement of each in turn, we find that Bull who wished to obtain color stimuli of equal saturation and brightness, merely states that he does this by establishing pairs of colors such that equal amounts of each cancel and give a gray that conforms to the standard gray he has chosen (A. f. O., 1881, XXVII., p. 95). Hess, aiming to obtain a red light such that its red *Valenz*, or, as he says, its capacity to arouse red sensation, is equal to the green *Valenz* of a green light, writes: "Als Nächstliegende erscheint es nun, einem roth- und einem grün-wirkenden Pigmente den gleichen Roth und Grünwerthe dann zuzuschreiben, wenn dieselben zu gleichen Theilen eine farblose Mischung geben" (A. f. O., 1889, XXXV., p. 39). Hegg wishing to equalize the color-values of his stimuli, claims that this is possible for only the two members of each pair of antagonistic colors. Red can be made equal in color-value to green, he says, or yellow to blue, but green and blue can not be equalized. He continues: "Wir betrachten ein *Roth* und ein *Grün* als chromatisch äquivalent, wenn sie auf der Rotationsscheibe zu gleichen Theilen gemischt sich gegenseitig total aufheben, so dass eine Mischung entsteht, welche weder ins rothliche noch grünliche sticht." (A. f. O., 1892, XXXVIII., p. 149). Baird offers no reason whatever for selecting the method of cancelling power by means of which to equate color-values. He apparently takes for granted that this method is the only one, and does no more than describe how the method was applied to his particular stimuli.

The search for a reason for this selection may, however, be pushed back a little further. We find that in 1880 before any of the work mentioned above was published, Hering (Lotos. Jahrbuch für Naturwissenschaft,

1880, I, pp. 76-107) had made statements from which we can conclude that in his opinion two antagonistic colors of equal sensation-arousing power cancel. Hering's statements leading to this conclusion are as follows: (a) 'Die Vermögen der Lichtstrahlen, die weisse Empfindung zu fördern, will ich die weisse Valenz der Lichtstrahlen nenne.' (p. 79.) (While this definition is not specifically repeated for colored light, still it is obvious from the text that it applies to colored as well as to white light).¹¹⁷

¹¹⁷ The following quotations are appended to show the use of *Valenz* by Hering and Hess:

Hering (Zur Erklärung der Farbenblindheit aus der Theorie der Gegenfarben. Lotos—Jahrbuch für Naturwissenschaft, 1880, I., p. 76-107) writes (p. 79): "Die Vermögen der Lichtstrahlen, die weisse Empfindung zu fördern, will ich die weisse Valenz der Lichtstrahlen nennen.

"Die Grösse dieser Valenz ist offenbar von zwei Factoren abhängig: ersten von der objectiven Intensität oder lebendigen Kraft, mit welchen die Strahlen verschiedener Wellenlänge bis zur empfindlichen Netzhautschicht gelangen, und zweitens von dem, was wir die specifische weisse Erregbarkeit des Sehorgans gegenüber den Strahlen verschiedenen Wellenlänge nennen, d.i. das Vermögen dieses Organs, unter dem Einflusse jener Strahlen die Weissempfindung deutlicher werden lassen.

"Ausser der weissen Valenz, welche allen Lichtstrahlen gemeinsam ist, kommen nun den einzelnen Strahlenarten verschiedene farbige Valenzen zu. Allen Strahlen vom aussersten Roth oder vom Anfange des Spectrums bis zu jenem im Tone reinen Grün, welches eine Gründfarbe ist und welches wir das Urgrün nennen wollen, haben eine gelbe, allen Strahlen vom Urgrün bis zum violetten Ende des Spectrums eine blaue Valenz."

Hess (Ueber den Farbensinn bei indirectem Sehen, A. f. O., 1889, XXXV., pp. 1-60.) writes (p. 30): "Unter weisser Valenz eines farbigen homogenen oder zusammengesetzten Lichtes versteht Hering den Helligkeitswerth desselben für eine Netzhautstelle, welche das farbige Licht wegen mangelhaften Farbensinnes oder aus anderen Gründen farblos sieht" (p. 39): "Um über das gegenseitige Verhältniss der Abnahme der Empfindungsvermögens für Roth und Grün, resp. Blau und Gelb überhaupt Untersuchungen anstellen zu können, ist es zunächst erforderlich, für beide Arten des Empfindungsvermögens ein gemeinsames Maass zu finden. Verschiedene grüne Lichter besitzten die Fähigkeit, grüne Empfindung zu erzeugen, in sehr verschiedenem Maasse, sie sind, um es kurz zu bezeichnen, sehr verschieden grünwirkend. Das mehr oder minder grosse Vermögen eines Lichtes, grün zu wirken, bezeichnen wir mit Hering als die grüne Valenz oder den Grünwerth des bezüglichen Lichtes". (p. 40): "Bestimmen und messen lässt sich derselbe nur in Bezug auf ein als Normalgrün gewahltes Pigment, welches unter genau denselben Beleuchtungsverhältnissen wie das zu untersuchende gesehen wird. Ganz analoges gilt von dem Roth-, Gelb-, und Blauwerthe eines Pigmentes.

"Für die vorliegende Frage handelt es sich aber nicht bloss darum die Grünwerthe oder die Rothwerthe verschiedenen Pigmente je unter sich zu vergleichen, sondern den Grünwerthe eines grünwirkenden mit dem Rothwerthe eines rothwirkenden Pigmentes.

"Als das Nächstliegende erscheint es nun, einem roth- und einem grünwirken-

(b) "Zwei homogenen Lichter, nun, von welchen das eine ebenso gelb (oder roth) wirkt, und das andere blau (oder grün) so dass beide Valenzen sich aufheben, nenne ich gegenfarbig äquivalent" (pp. 83-84). In the first of these statements he directly calls the capacity of a color to arouse sensation its *Valenz*. And from the second it may readily be derived that when the yellow-sense, for example, is affected as strongly by yellow light as the blue-sense is affected by blue light, complete cancellation will ensue,—that is, equality in cancelling power may be considered as the equivalent of equality in capacity to arouse sensation. In making this deduction we have of course assumed that *wirkt* refers to sensation-arousing action and not to cancelling action. We have no doubt that this assumption is correct, still it may be worth while to bring forward direct evidence in support of this point from a statement made by Hess while working under Hering's direction. Hess writes: "Das mehr oder minder grosse Vermögen eines Lichtes grün zu wirken, bezeichnen wir mit Hering als die grüne Valenz oder den Grünwerth des bezüglichen Lichtes" (op. cit., p. 39). Here *Vermögen grün zu wirken* is made the equivalent of *Valenz* and *Valenz* by definition is the capacity of a color to arouse sensation. Hence we have little hesitation in assuming that in the case in question *wirkt* also refers to the sensation-arousing action of the colored light and not to its cancelling action, and in concluding, therefore, that Hering believed that antagonistic colors of equal power to arouse sensation would also have equal power to cancel each other. Since this is true, it is probable that the followers of Hering (Hess and Hegg) assumed the equivalence of power to arouse sensation and power to cancel and equated their stimuli accordingly. That Hess was actuated by some such reason is shown by a statement made by him in his discussion of this point. He writes: Die von Herrn Professor Hering angegebene, oben geschriebene Untersuchungsweise gestattet mit grosse Genauigkeit den zu vergleichenden Pigmenten gleich grosse farbige und gleich grosse weisse Valenz zu geben, sie ermöglicht es, für die Werthigkeit der Farben einen genauen numerischen Ausdruck zu gewinnen und in die Rechnung einzuführen" (op. cit., p. 58). Hegg also seems to refer back to Hering, for he uses the Hering terminology in discussing the equation of his stimuli.

Or (b) since cancellation is the corollary to the assumption of an assimilation-dissimilation mechanism, it may have been considered for some reason, not readily understood by the writer, that an equation based upon it is the proper one to make.

Having said this much about the impropriety of selecting a subjective measure for the intensity equation of stimuli, let us

den Pigmente den gleichen Roth-und Grünwerth dann zuzuschreiben, wenn dieselben zu gleichen Theilen, z.B. auf dem Kreisel gemischt eine farblose Mischung geben, im Falle sie dazu aber in einem anderen Verhältnisse gemischt werden müssen, anzunehmen, dass sich der Rothwerthe des einen zum Grünwerthe des anderen umgekehrt verhält wie die Grösse der beiden zur Herstellung einer farbosen Mischung nöthigen Sektoren."

pass to a résumé of the attempts that have been made to apply this measure by Bull, Hess, Hegg, and Baird. Hegg selected four stimuli that suffered no alteration of color tone in passing from the center to the periphery.¹¹⁸ These were a bluish-red, a bluish-green, a blue, and a yellow. They were equated in pairs, the bluish-red to the bluish-green, and the blue to the yellow, as follows. It was determined in what proportions the members of each pair had to be combined to produce gray, and from these proportions, values of the sectors of the stimulus disc were calculated for each color. The procedures of Bull and Hess were essentially similar..

Baird, employing the light transmitted by gelatines, prepared blue, yellow, red, and green stimuli as follows. A lantern containing an incandescent lamp of 16 candle-power was used as source of light. The stimulus light was emitted from the lantern through a circular aperture, 15 mm. in diameter. Gelatines were placed over the aperture in combinations which gave the four stable colors, and their spectral values were obtained. A disc in which two windows of equal size had been cut, was rotated on a motor in front of the lantern. The combination of gelatines to give the red stimulus was fastened across one of the windows, while the green combination was used to cover the other window. As the windows were of equal size, the rotation of the disc gave a mixture which contained equal proportions of both stimuli. The gelatine combinations were changed by adding, subtracting, or substituting until the mixture showed no trace of color. Similar equations were obtained for the blue and the yellow stimuli.

It will be seen from the work of these men that even if their methods had been based upon a proper principle of equating, they would not be adequate for all that is involved in the problem

¹¹⁸ Only one meridian was used for determining this invariability of color tone. It is obvious that a conclusion should not be drawn from such a scant investigation of the sensitivity of the retina. For example, working with the red, green, blue, and yellow of the Hering standard papers, the writer has found that with a careful standardization of factors, an investigation in any considerable number of meridians shows that stability of tone is possessed by the blue alone.

of determining the comparative sensitivity of the retina to the different colors. For not only is the comparative sensitivity to the complementary colors desired, but to the non-complementary colors as well. The method offers no possibility, for example, of equating red and green to blue and yellow. One can only conjecture how much of our present conception of the comparative extent of the different zones of color sensitivity is an artifact due to the use of stimuli that have not been equated with reference to the energy of the light-waves they give to the eye. In addition, then, to the objection that the methods that have been used thus far to equate the color stimuli in intensity are found to be essentially wrong in principle, the further criticism may be offered that they are not adequate in scope. An energy equation of the light-waves by means of some radiometric device, for example, the thermopile, the bolometer, the selenium cell, or what not, alone seems adequate to the requirements set by the problem of determining the comparative sensitivity of the retina to the different colors, or the comparative limits of the zones of sensitivity.

Energy equations in terms of radiometric units have been made by Langley and Pfund, but up to this time no investigation of color sensitivity has been made with colors equalized in energy. Langley¹¹⁹ invented the bolometer and determined by means of it the relative distribution of energy in the normal spectrum. In order to equalize the energy of the different colors, he states that one may vary the width of the collimator-slit until equal radiometric readings are obtained. In his own experiments on visual acuity, he does not, however, proceed in this way. Tables of logarithms were illuminated in a dark-room by monochromatic light representing known amounts of energy. The greatest distance at which the figures could be read was determined for each of the colors, and corrections were applied for inequalities in the energy of the different lights. The corrections were made in terms of the distribution obtaining in the following table.

Pfund used the first method suggested by Langley. In an

¹¹⁹ Langley. *Energy and Vision*. Amer. Journ of Science, 1888, XXXVI., 3rd Ser., pp. 359-379.

investigation of the changes in the resistance of selenium to lights of varying wave-length, he employed differently colored

Wave-length	μ .35	μ .38	μ .45	μ .50	μ .55	μ .60	μ .65	μ .70	μ .75	μ .768
Heat	1.8	5.3	11.9	17.3	20.7	21.9	22.2	21.4	20.7	20.2

beams of equal intensity. The intensity equations were made as follows. Using first a Rubens thermopile¹²⁰ and later a radio-micrometer,¹²¹ Pfund determined which wave-length gave the least galvanometer deflection. He then reduced the more intense beams by interposing a smoked wedge of the proper thickness until every portion of the spectrum produced the same deflection. In this way he obtained colored lights of known and constant energy.

Psychological investigators have been slow to recognize the importance of standardization of intensity in radiometric terms of the colors which are to be used for the investigation of sensitivity. The only equations of intensity have been made in subjective terms, a procedure which if done by a proper method may be legitimate for work on certain points relative to existing color theories, but which is not adequate (see this paper, pp. 64-65) to meet the requirements of the problems which deal with the comparative sensitivity of the retina to the different colors.

Note.—Since the completion of this paper, the report of Watson and Yerkes concerning methods of studying vision in animals has been published (*Behavior Monographs*, 1911, I, pp. 1-89). For the measurement of the intensity of the stimulus they find two methods available, photometry and radiometry. They write: "The method of photometry in all its forms is dependent upon the visual capacity, training, and the special skill of the observer who attempts to use it. For this reason, and others only less important, it is usually desirable to supplement photometric measurements of photic stimuli by measurements of their value in terms of energy. Hence the pertinence of physical measurements. Determination of the value of photic stimuli in terms of heat units by radiometric procedure has proved feasible. Radiometry yields a measurement which is relatively independent of the visual peculiarities of the observer, and it therefore supplements in an invaluable manner the results of photometry" (p. 11).

The authors in question then decide in favor of radiometric measurement

¹²⁰ Pfund, A. A Study of the Selenium Cell. *Philos. Mag.*, 1904, VII, Ser. 6, p. 26.

¹²¹ Pfund, A. The Electrical and Optical Properties of Metallic Selenium. *Phys. Rev.*, 1909, XXVIII, p. 326.

and control of the stimuli to be used in determining the animal's color sense. Their reasons for this decision are not, however, those stated in the above criticism of subjective methods of equation either by cancelling power or by sensation-arousing power, namely, that these methods are essentially wrong in principle for tests for the comparative sensitivity of the eye to different colors. That they do not consider them wrong in principle for work of this kind is shown in fact by their recommendation of the Hegg colored papers. The colors of the Hegg papers are equated in intensity in terms of the cancelling power of the complementary colors, the worst of the subjective methods discussed. They write: "These [the Hegg papers] are mixtures of oils on paper yielding the hues red, yellow, green, and blue. These hues are claimed to be equal in intensity and saturation for the human eye. The set is useful as a means of ascertaining, in a preliminary survey, whether an animal readily discriminates two hues which for us are of nearly the same intensity and saturation" (p. 32). It is obvious also that they do not consider the photometric method of equating intensities (also a subjective method) wrong in principle. The method is not recommended merely because it depends upon the visual capacity, training, and special skill of the observer. But the fact that they endorse this method to supplement the radiometric procedure or rather, as quoted above, the radiometric to supplement the photometric shows that they do not realize the absolute diversity of the photometric and of the radiometric curve. Their conclusion, then, in favor of the method of radiometry for measuring the intensity of the stimulus is based upon very different arguments from those which have governed the similar decision reached in the above discussion. They do not seem to entertain any criticism of the subjective method of equating, either the method which measures cancelling power, or the method of photometry, nor do they recommend that either be discarded. Their choice of energy measurement is due largely to the fact that they wish a method which is as free as possible from subjective errors.

3. *Brightness of the Stimulus*

The same investigators who sought to obtain stimuli of equal intensity, attempted also to equate these stimuli in brightness. This may be done in two ways: the white-values of the colors as they appear in direct vision may be equated, or the white-values as they appear in indirect vision may be equalized. The first method was used by Bull who made direct comparison judgments of the relative brightness of the colors, facilitating his comparisons by the use of intermediate color-tones. For example, a blue was changed in brightness until it appeared as light as a given blue-green. Green was then made equal to the blue-green; yellow-green to the green; yellow, to the yellow-green, etc. Hess, Hegg, and Baird employed the second

method. The stimuli were carried to a point in the field of the peripheral retina at which they appeared colorless and their brightness values were altered until the gray sensations obtained from all the stimuli were equal.

Hegg, who used pigment colors, observed the stimulus through an opening in a gray screen, whose brightness could be altered by turning it toward or away from the source of light. He adjusted the screen so that its brightness was the same as that of the gray sensation aroused by the green stimulus in the peripheral retina. Retaining this setting of the screen, he replaced the green by the red stimulus, the intensity of which he had previously equated to the intensity of the green by the method described and criticised in the preceding section. The red stimulus, which was composed of 216° of red, 55° of blue, 89° of white, when observed in the extreme periphery, was seen as a gray that was lighter than the screen. To make the stimulus and the screen of equal brightness, 5° of the white sector had to be replaced by black. A complication arose when blue and yellow were equated to this brightness, resulting from the changes in color-tone which took place. Hegg found that when he added white to lighten the blue stimulus, a sensation of reddish-blue was aroused. (Chodin, it will be remembered (see p. 45), saw in this fact an argument against the possibility of equating the brightness of colors for investigations of this kind.) To cancel this effect, he added green. The addition of black to yellow, which was necessary in order to equate the brightness of yellow to green, resulted in a greenish-yellow sensation. To this he added red in a sufficient amount to cancel the greenish appearance of the fusion.¹²²

¹²² In connection with a study (done in cooperation with Dr. C. E. Ferree) to determine the physiological level at which the fusion of colored with colorless light sensation takes place, the writer attempted to add sufficient red to cancel the green in a mixture of yellow and black. A curious paradox was observed. Starting with 55° of yellow, and 305° of black, and keeping these proportions relatively constant while red was being added to the mixture, it was reported by a number of observers that, after the addition of about 10° of red, it was seen in the mixture with the green. As more was added, the green and red continued together in varying proportions, until, with about 45° of red in the mixture, it dominated the fusion, which was seen as a dark brownish-orange. Our ob-

Hegg does not give the proportions of the final white-green-blue *Urblau* and the black-red-yellow *Urgelb* which, he claims, were equal in brightness to the *Urroth* and *Urgrün*.

Baird also used the method of indirect vision comparison. The two stimuli to be equated were placed one above the other at a point at which both appeared colorless in the periphery of the retina. The brightness of blue was chosen as standard, and the red, green, and yellow stimuli were darkened to equal it by rotating an episcotister in front of each of them in turn. The sectors of the episcotister were adjusted so that each stimulus was darkened as much as necessary to cause the colorless sensation aroused by it in the periphery to be the same as was aroused by the blue stimulus. Baird does not say that his work was complicated by changes in color-tone. His method would at first glance seem to be more simple than that of Hegg. When, however, we remember that the equation of brightness and apparent intensity had to be carried on hand in hand, we see some of the difficulties he must have encountered. His problem, was to bring the complementary colors to such intensity, that 180° of one cancelled 180° of the other; and at the same time, to maintain them all of the brightness of the blue. But it is apparent that by his method of equating in brightness, an alteration in the amount of colored light coming to the eye is produced every time a change in brightness is made. And as the brightness of the several stimuli had to be changed by unequal amounts to bring them all to the brightness of blue, the amount of colored light coming to the eye was also changed by unequal amounts. This much of the procedure is sufficient to show the difficulty that confronts the experimenter. To equate either for brightness or cancelling power, disturbs the equation established for the other; that is, when the stimuli are brought to equal brightness, their cancelling power will no longer be equal, and *vice versa*. It is obvious that

servation has been verified too many times and by too many observers for us to question its validity. It stands, then, in direct contradiction to Hegg's claim that a change in color-tone produced by altering the white-value of a color can be remedied by adding the complementary color to the stimulus. The difficulty then, seems insurmountable, and stands as one of the objections to the attempt to equate colors in brightness.

the goal desired, if it can be attained at all, must be reached by a series of approximations; and that in the end the experimenter will have very much altered stimuli. Since to equate for both at once, involves making much more radical changes in the stimuli than to equate for one alone, it is plain that in doing both, we but add to the objections we have already made when each is done alone.

It is to be deplored that Baird does not tell us just how he worked in this most difficult part of his technique. The defect is serious, for as the report of his method stands, one can neither pass judgment on its adequacy, nor be sufficiently guided by it, should one attempt to repeat the work. Of the technique that is described, however, the following criticism may be offered. In the equation of the brightness of two stimuli, Baird carried them to an angle of excentricity, at which both appeared colorless. Now, it is seen from his tables, that the limit of blue is some 15° wider than that of green. He has, then, either to show that the brightness of green is the same at its limit as it is 15° peripheral-wards, or to equate the brightness of the colors at their individual limits by some means, such as the flicker method.

Since Bull equated his stimuli by the direct vision method, and Hess, Hegg, and Baird by the indirect vision method, a word may be said in concluding this topic with regard to which is the proper method. Obviously, the decision rests upon whether or not the colors have different relative white-values at center and periphery. That they do has been reported among others by Tschermak,¹²³ and we have been able to confirm this statement. The equation should, therefore, be made in the peripheral retina. As we shall show in the experimental section of our paper, however, no equation should have been made by any of these men for the work they were doing, because unless the stimuli used are extremely weak in saturation, to equate in brightness for the investigation of the limits of sensitivity not only is unnecessary, but results in positive harm. If, however, in other work in the peripheral retina the need for equating should arise, the writer would urge not only that the equation should be made in the

¹²³ Tschermak, A. op. cit., pp. 564-575.

peripheral retina, but that it should be obtained at the point at which the investigation is to be made.

c. Summary.

With regard to the attempts that have been made to standardize, the results of our historical survey are found to be largely destructive in character. They show, however, that a decided need for standardizing has been recognized. This in itself was a first step in the right direction. The following factors have been discussed: (a) *The size of the stimulus.* This factor has been the most adequately treated by previous investigators. Its influence as a factor has been shown, and with it the need of careful measurement of the actual size of the stimulus and of its apparent size as determined by its distance from the eye of the observer. There is still need, however, for further work. While it has been generally held that an increase in the area of the stimulus functions in some degree as the equivalent of an increase in intensity, and thus influences the limits and limens of color sensitivity, no quantitative estimate has been made of the degree of this equivalence. Exact knowledge of this point is not only of general interest in psychological optics, but it is needed in turn in certain problems of standardizing. For example, it is often required that the size of the stimulus be varied and its intensity for sensation be kept constant. This can be done only when the ratio of equivalence is known. As stated on p. 6, this ratio is now being worked out in this laboratory. The results will be reported later.

(b) *The intensity of the stimulus.* The influence of the intensity of the stimulus upon color limens and color limits has been pointed out, but no adequate standard of measure has been employed. In dealing with the comparative sensitivity of the retina to the different colors, estimated in terms of the limits, it is obvious that equal amounts of light should be used. Estimated in terms of the limens, the amounts used should be determined in terms of units that can be compared. The problem of the measurement of these amounts of light is wholly physical, hence the standard of the physicist should be adopted. The determination should be in terms of energy as measured by the bolometer,

the thermopile, or other radiometric device. Only in this way so far as we know, can the retina's sensitivity to the different colored lights be obtained in terms of units that can be compared.

(c) *The brightness of the stimulus.* Brightness and intensity have been much confused in the literature of the subject. The effect obtained by varying both factors has often been attributed to change in brightness alone. The effect of change in brightness has never been investigated in isolation. This factor, then, occupies the novel position of having been standardized for work on the limits of color sensitivity before the need for such control has been shown.

(d) *The preëxposure.* Only in a very general way has the effect of the brightness of the preëxposure been recognized, and the precise reason for its influence has been very little understood. No quantitative estimate of the effect has been made, and no attempt at standardization has been undertaken which has shown any comprehensive knowledge of how the factor works.

(e) *The field surrounding the stimulus.* Considerable attention has been given to this factor. A small amount of qualitative work has been done, and some attempts have been made to secure control of the factor. More detailed knowledge, however, is needed of its influence, quantitative and qualitative, over a wider range of the retina. Especially should its relation to general illumination be studied. Until this relation is understood and some means is taken to render the general illumination constant, no effective estimation of the influence of the brightness of the surrounding field can be obtained, nor can it be eliminated as a factor from the color observation.

(f) *The general illumination.* The influence of the illumination of the visual field on color sensitivity has been recognized and rough attempts have been made to determine the amount of this influence. The different ways in which changes in general illumination affect color sensitivity have not, however, been determined, and the relative importance of each has not been estimated. Very little attempt at standardization has been made because the first essential of standardization, namely, a sensitive means of measurement, has not been had.

III. EXPERIMENTAL.

A. PURPOSE OF INVESTIGATION.

The purpose of this investigation includes the following points. (1) The color observation will be analyzed for the brightness factors that influence its results. (2) A systematic study will be made of these factors with special reference to the determination of their effect upon the color sensitivity of the retina and upon the limits of sensitivity to different colors. (3) It will be ascertained whether the effect of these factors can not be explained in terms of the action of brightness upon color in the peripheral retina and of the rapidity with which the sensitivity to color decreases from the fovea outwards. (4) Methods will be devised to standardize these factors in so far as our results show the need of standardization. No attempt will be made at this point to study the factors that pertain to the source of light with the following exception. Brightness will be isolated from intensity and the effect on the limits of sensitivity of changes in the brightness of the stimulus, made without altering the amount of colored light coming to the eye, will be determined in order to find out whether or not colors should be equated in brightness when the limits of sensitivity are investigated. Moreover, since our problem is concerned only with the brightness factors that influence the action of the colored stimulus upon the retina, the writer will not feel obliged to concern herself with the standardization of her stimulus with regard to either quality or intensity any further than is needed to show the effect of the brightness factors upon the retina's response to these stimuli. All the standardization that is needed will be accomplished by using the same stimulus for all observations the results of which are to be compared; that is, no comparisons will be made except of the effect of the different brightness factors upon the same stimulus. For obtaining results so purely comparative the standardization afforded by pigment papers should be adequate, provided a standard illumination can be obtained so that the amount of

colored light reflected from the pigments will be constant from test to test. Since we were able to secure a highly sensitive means of duplicating our illumination from observation to observation, the standardization of the stimulus afforded by the Hering pigment papers has been considered adequate. More especially has this degree of standardization been considered adequate because the results are to be used primarily merely as a guide in the formulation of a method of working. Having secured a method of working, however, that will permit of a close duplication of results from observation to observation with the pigment papers, the writer will attempt to adapt the method to work in which the colors of the spectrum are used. In order to do this, the following requirements will have to be met. (1) A spectroscope will have to be devised by means of which the retina can be stimulated at any degree of excentricity in any meridian that is desired, for example, a spectroscope that can be used in conjunction with the rotary campimeter¹ in all its adjustments. Such a spectroscope having all the freedom of movements of its parts needed for use with the rotary campimeter has been devised in this laboratory and is now under construction. (2) In order that the stimulus-opening in our campimeter be filled with light sufficiently homogeneous for our purpose, a prism of high dispersive power will have to be procured for use in our spectroscope. A compound prism of the Cassie type² seems adequate for this requirement. Such a prism constructed to our special order is now being made for us in Germany. (3) In order that the light may undergo high dispersion and still be sufficiently intense for work in a room lighted to the degree that some phases of our problem demand, a source of light of high intrinsic brilliancy is needed. Constancy in candle-power should also be had. A high voltage Nernst filament seasoned for 100 hours or more and operated on a steady circuit will give, the writer believes, the intensity and constancy required.

Having completed our work of standardizing the factors extraneous to the source of light, an attempt will next be made

¹ For a description of the rotary campimeter see this paper p. 87 ff.

² Cassie, *Philos. Mag.*, 1902, III. Ser 6., p. 449.

to secure a better control of the source. Standardization up to the present can be considered successful only with regard to the quality of light. No adequate work has been done on the standardization of the quantity of light for work on color sensitivity. As stated earlier in the paper, the writer believes that this can be done only by means of energy determinations. She expects to do her radiometric work by means of a surface thermopile (Coblentz model)³ and a DuBois-Rubens *Panzer galvanometer*, unless future results show that some other combination of radiometer and galvanometer is more satisfactory.

Finally from the work of standardization it is our hope to return to the investigation of the problems which we were in the beginning forced to abandon because the work could not be satisfactorily done by the methods now in use in the optics of color. A brief statement of the plan of our future work has already been given in an article published in conjunction with Dr. Ferree in the *American Journal of Psychology*.⁴ In order that the scope of this work be known at this point, and that the importance of the present investigation be understood in relation to this work, the statement is appended here.

"About a year ago⁵ the writers undertook to determine the retina's sensitivity, relative and absolute, to colored light in terms of units that can be compared. Since several years will be required to complete this work, they have thought it best to publish a preliminary note showing briefly the purpose and scope of the investigation. The following points will serve to indicate what is being attempted in this study.

"(1) All measurements of sensitivity will be made in radiometric terms. This will give an expression of the sensitivity of the retina in units which are directly comparable with one another. At present we have no direct estimate of the comparative sensitivity of the retina to the different colors further than is ex-

³ Coblentz, W. W. Instruments and Methods Used in Radiometry. Reprint No. 188, Bulletin of the Bureau of Standards, 1911, IX., pp. 22-23.

⁴ Ferree, C. E. and Rand, G. A note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units. *Amer. Journ. of Psychol.*, 1912, XXIII, pp. 328-332.

⁵ The first public statement of our intention to use radiometric units in the investigation of the retina's sensitivity to color was made to the committee in charge of the Sarah Berliner Research Fellowship, February 1, 1911.

pressed, for example, by the relative width of the collimator-slit that has to be used to arouse color sensation when a light-source of a given candle-power is used. This kind of comparison is obviously unfair because such different amounts of energy are represented from point to point in the spectrum that a given width of slit would admit many times the amount of energy at one part of the spectrum that it would at another. In short, no adequate estimation and expression of the retina's sensitivity to color, comparative or absolute, can be made by means of the methods now in common use.⁶

“(2) Comparisons of results on many other points with such disparate stimuli seem equally inadequate: the relative time required for the different color sensations to attain their

⁶Two criticisms have been received from private sources which it may be well to take account of here. In one the possibility of a point of view is implied, in the other a point of view is stated. The point of view, the possibility of which is implied in the first criticism, is that it is not proper to estimate the sensitivity of the retina in terms of physical units, because it is generally conceded by modern investigators of color vision that the retinal processes which transform the physical energy of the color stimulus into nervous energy is essentially chemical in its nature; and one can not assume that a certain amount of physical energy arouses an equal amount of chemical energy in the retina, nor that equal amounts of physical energy arouse equal amounts of chemical energy. In answer to this, the writers would point out that these chemical substances are a part of the retina and their respective inertiae constitute one set of factors that determine the sensitivity of the retina to the different colored lights. It is not necessary to assume, therefore, that a given amount of physical energy arouses an equal amount of chemical energy, etc., in order to make our determinations of the comparative sensitivity of the retina to the different colors in terms of physical units. That would be necessary only if we were trying to separate out the nerve filaments, and to measure or compare their sensitivity to the different colors in terms of physical units. But even in chemical theories when speaking of the comparative sensitivity of the retina to the different colors, we do not mean the comparative sensitivity of the nerve filaments alone. We include the reaction of the chemical substances as well. Our contention, then, is that if the determination of the comparative sensitivity of the retina to the different colors is a proper problem, the determination should be made in terms of quantities that can be compared. This can be done either (a) by using lights equalized in energy and determining by means of a sectorized disc the relative amounts of these lights that are required to arouse sensation; or (b) by using lights representing different amounts of energy and measuring directly in terms of radiometric units the amounts required to arouse sensation. We scarcely need point out that in speaking of the comparative sensitivity of the retina to the different colors we are not raising a new problem, but are merely recognizing a very old one.

The second criticism is in substance that a quantitative comparison of the effect of the different wave-lengths on the retina is improper because the different wave-lengths constitute stimuli too different in kind to permit such comparison. This criticism we leave open, because we do not wish to discuss in this paper the propriety of the problem of comparing sensitivities.

maximum of intensity, or retinal inertia; the relative rate of fatigue to the different colors; after-image and contrast sensitivity, etc.⁷ In fact there is not a quantitative problem dealing

⁷It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amount of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse positive sensation. If the former view should be held it will be convenient to start with stimuli equalized in energy, and to determine the relative amounts of light required to arouse the after-image or contrast sensation by means of a sectorized disc. If the second view should be held, the energy of the lights used may first be rendered proportional to the sensitivity of the eye to the colors in question; and the liminal values may then be determined by means of the sectorized disc. In each case the relative sensitivity may be expressed by the inverse ratio of the open to the closed sectors.

Similarly two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy of the lights may be made inversely proportional to the sensitivity of the eye to the different colors.

The need in both the above cases is equally great for a method of regulating and determining the amounts of light to be used in terms of a common unit of measurement. For example, in the second case two ways might be conceived of making the amounts of the colored lights proportional to the eye's sensitivity to these lights. (1) The limens might be determined and the intensity of the lights always be kept directly proportional to these liminal values. But the ratio needed to maintain this proportion could not be established unless some means were available of measuring the limen-values in terms of a common unit. And if this were established, we have no right to assume that it expresses the relative sensitivity of the eye to the colors in question when greater amounts of light are used. To make this assumption, we would have to maintain (a) not only that Weber's law holds for colored as well as for white light, but also that the ratio of increase which gives the just noticeable change in intensity is the same for all colors. We do not even know that there is a constant ratio over any considerable range of the intensity scale for even a single color. (b) We would have to maintain that this ratio is the same at the limen as at greater intensities, in other words, that Weber's law holds down to the limen. The consensus of opinion among investigators is that this is not true. (2) A curve may be constructed for the particular observer in which just noticeable changes in sensation are plotted along one coordinate and the energy changes required to give these changes in sensation are plotted along the other coordinate. The subjective equation, then, would be made by choosing points on the curves for each of the colors all representing the same number of just noticeable changes in intensity of sensation from the limen. The amounts of light required to give these equally intensive sensations could then readily be read off from the energy coordinate of the curve. The energy measurements required to construct such a curve would be comparatively simple, for once the limen-value was measured in terms of energy units, the remainder of the values could be determined by means of the sectorized disc, that is, the energy change required to produce a just noticeable change in sensation is directly proportional to the ratio of change of open to closed sectors in the disc.

with the comparative functioning of the retina to the different colors in which there does not seem to be a need for the regulation and estimation of the stimulus in terms of a common unit of measurement. It is the purpose of the writers to extend the work as fast as possible into these related fields.

“(3) We wish to make a careful study of the sensitivity of the peripheral retina, quantitative^s and qualitative, in a large number of meridians. In general too much uniformity has been assumed with regard to the sensitivity of the peripheral retina.

^sThe following are two of the points we wish to take up: (1) A determination will be made of the ratio of sensitivity of peripheral to central retina from point to point for a single color in several meridians. This will show at what rate the retina falls off in sensitivity in a single meridian, and how uniform this decrease is in the different meridians. We have found in a preliminary study that this knowledge is greatly needed in explaining certain phenomena of the peripheral retina. Furthermore, when this determination is made for each of the colors with which we wish to work, the ratios of sensitivity for these colors at all the points can be calculated and a definite answer can be given to the question whether or not uniformity of ratio obtains throughout the retina. This question has been given considerable importance in the discussion of color theories. (2) The limits of sensitivity will be investigated. In general two problems are involved here. (a) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (b) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors. The second problem is more complicated and will later be made the subject of a separate paper. A word indicating its relation to our present plan of work may, however, not be out of place here. It may be logically assumed, for example, that the Hering theory demands that wherever the blue-sensing substance is found, the yellow-sensing substance must also be found. We have no means of knowing where these substances are except by the sensation aroused. Speaking in terms of the theory, then, we have a right to assume that wherever the blue sensation can be aroused the yellow sensation should be able to be aroused also, provided a sufficiently intensive stimulus be used. If, therefore, in passing towards the periphery of the retina, a point be found where blue can be aroused and yellow can not, the evidence will be strongly in favor of the conclusion that no yellow substance is present, unless it can be shown that elsewhere in the retina so much greater energy of yellow light than of blue is required to arouse sensation that the amount needed for this far peripheral point is greater than can be obtained. To establish this point the comparative sensitivity to these colors would have to be obtained at various points in the retina. This would involve the determination of a ratio based upon the amounts of blue and yellow light required to arouse sensation. Two methods of measurement may be used. (a) The amounts needed may be measured directly by means of a thermopile of the type we use, or other sensitive radiometer. In a determination of limens the number of readings required would render this method tedious. (b) The energy of the two lights may be made equal by means of a thermopile and the final amounts required to arouse sensation may be secured by means of a sectored disc. From the ratio of open to closed sectors the amount the light is cut down in each case may be calculated and the ratios of energy may be determined from these amounts.

Generalizations of great importance to color theory have frequently been based upon the results of work in which careful investigation was made in only one or two meridians. The conception of stable colors, and its application in support of the Hering *Urfarben* may be taken as a fair example of a sweeping conclusion which is based upon work too limited in its range. With a careful standardization of factors, an investigation in any considerable number of meridians shows that stable colors do not exist.⁹ Many other points of interest have come out in our more detailed study of the peripheral retina. For example, we find in the periphery of the normal retina small areas which are exact replicas of the Schumann case of color-blindness.

“(4) We wish to conduct our investigation in full daylight instead of in the dark-room. This is to eliminate the influence of the field surrounding the colored stimulus and of the pre-exposure. When the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness, the induction takes place in different amounts for the different colors. This white, in proportion to its amount, reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. To eliminate this twofold unequal action, the surrounding field should be made in each case of the brightness of the color to be used. This can be done by working in a light-room of constant intensity of illumination and making the surrounding field of a gray paper of the brightness of the stimulus color. In order to accomplish this, and at the same time be able to work upon any meridian of the retina we choose, we have constructed a special piece of apparatus which we call a rotary campimeter. The influence of preexposure is even more important than of surrounding field. If the preexposure is too black, white is added as after-image to the stimulus color. The effect of a black preexposure upon the stimulus color is greater than the effect of a surrounding field of black, because more

⁹ The following points are offered in support of the above statement. (1) A red and green cannot be obtained which in every meridian of the peripheral retina will pass into gray without an intermediate change into yellow or blue. (2) The amount of blue that has to be added to a mixture of red and green to produce gray varies from point to point in a given meridian even where the extramacular region alone is considered. Further, a series of determinations made for a given meridian will not hold for the remaining meridians. (3) A red, green, and yellow can not be obtained which will not change in color-tone in passing from the center to the periphery of the retina in a single meridian.

Blue alone of the four principal colors is stable in tone for all parts of the retina.

white is added as after-image of preëxposure than is induced by contrast from the surrounding field. This effect also can be eliminated only by working in a light-room of constant intensity of illumination and by choosing as preëxposure a gray of the brightness of the color to be used."

B. DESCRIPTION OF OPTICS-ROOM AND APPARATUS.

The work was carried on in a well-lighted optics-room, $12\frac{1}{2} \times 10$ ft. The room is situated on the upper floor of an isolated building and is lighted by a skylight, $8 \times 7\frac{1}{2}$ ft. Beneath the skylight, two diffusion-sashes, $4 \times 7\frac{1}{2}$ ft. are swung on hinges so that they can be raised or lowered as desired. The framework of these sashes is made of a light-weight iron. For convenience of local control of illumination, if needed, each sash is divided into four units by means of cross-pieces. The sashes are filled with double-strength glass ground on one side, so adjusted to the frame that they can be removed easily for cleaning or for the substitution of some other kind of glass in case that is desired. This glass diffuses the light so effectively that local shadows cast by the cross-pieces in the framework of the skylight are completely eliminated, while the sudden changes of illumination produced by the passage of the sun behind a cloud are reduced to a minimum. This diffusion seems to have the further advantage of reducing the yellowness of direct sunlight below the limen of sensation. At least, when working under the sash, the observer never judged a gray exposed through the campimeter-opening as yellow under any local conditions, as frequently happened when working under direct sunlight.

The room is planned also so that small changes of illumination can be produced, ranging from the intensive illumination of a south-exposure skylight to the blackness of a moderately good dark-room. Two provisions are made for this. (a) The diffusion-sashes are made so that any or all of the panes of ground glass can be quickly and easily taken from the sash, and anything can be substituted that is desired; or the illumination can be varied by placing layers of tissue-paper above the glass. (b) The room is provided with two curtains mounted on heavy spring rollers. One is a white curtain made of thin muslin; the

other is a black light-proof curtain so mounted that, when drawn, its edges are deeply enclosed in light-proof boxing extending along the four walls of the room. One or both of these curtains can be drawn any distance that is desired, and the illumination can thus be changed gradually from a very intense brightness to a fairly good blackness. To aid in getting dark-room effects, the doors of the room are carefully boxed and curtained. One requirement of a perfect dark-room, however, is lacking, namely, the walls and floor of the room are painted white. This is because it is of advantage in the light-room work, and because complete blackness is not needed in the type of work for which the room is devised.

The apparatus used in the investigation consists of a rotary campimeter devised to meet the requirements of the task in hand by Dr. C. E. Ferree¹⁰ of Bryn Mawr College. The object of this apparatus is to add to the vertical campimeter the rotary features of the perimeter and thus to allow investigation of every possible meridian of the retina with as much ease and precision as was possible with the old form of campimeter in the nasal meridian only, or at most, in the nasal and temporal meridians. The apparatus consists of two parts with proper supports and accessories; a stimulus screen, and a campimeter screen which rotates on a collar around a circular support. The stimulus is exposed through an opening in the center of the campimeter screen. One arm of the framework of this screen carries the fixation-points, and also a right-angled extension which allows fixation to be given at an excentricity of 92° . This arm may be rotated to any position desired, and thus any meridian of the retina may be explored. In order that the sensation received in the peripheral retina may be accurately expressed in terms of color- and brightness-values of the central retina, the fixation-arm of the screen is further provided with a small detachable motor upon which may be rotated the proper combination of discs for matching peripheral sensation. This increases greatly the definiteness of work on the sensitivity of the peripheral retina.

¹⁰ For the original description of this apparatus, see C. E. Ferree. Description of a Rotary Campimeter. *Amer. Journ. of Psychol.*, 1912, XXIII, pp. 449-453.

The feature was added to the apparatus so that complete maps might be made of the changes in the sensitivity of the retina from center to periphery and from one meridian to another, with tables showing the value of the changes from point to point.

Photographs of the skeleton apparatus and of the front and back views of the campimeter in readiness for use are appended.

Figure 1 shows the skeleton apparatus. It consists of the following parts: supporting base, frame for campimeter screen, and frame for the stimulus card. The supporting base consists of a horizontal steel bar, 83 cm. long, supported by two iron tripod rests (B and B'). To this bar are clamped two uprights (C and C'), which are adjustable along its length. The anterior upright (C) supports the frame on which the background of cardboard and the campimeter screen (D) are fastened. The posterior upright (C') supports the stimulus frame (E). The height from the table of each of these frameworks is adjustable by means of set-screws (F and F'). The framework for the campimeter screen consists of central support and radiating arms. The central support consists of a stationary brass ring,¹¹ about which rotates a larger brass collar (H), 20 cm. in diameter. The back surface of collar (H) is graduated from 0° to 360°. To this collar are fastened the radiating arms. There are eight of these arms, one for each 45° mark of the graduated collar. They are made of steel and are 2 cm. broad and 40 cm. long. The eighth arm (I-I') differs from the other seven. It forms a right angle, one side of which is in the plane of the background and the other in front of this plane. The part in the plane of the background is 30 cm. long, and the part at right angles to this

¹¹ This ring was made large in diameter for two reasons. (a) The ring had to be made very thick in order to give sufficient rigidity to support the campimeter screen and to furnish proper attachment for the rotary collar. Had the circumference been small, the effect of the ring would have been that of a short tube. If the stimulus were viewed through a short tube, an induction factor would have been involved which would have been difficult, if not impossible, to standardize. The opening in the ring was, therefore, made considerably larger than any stimulus we wished to use in order to avoid the introduction of this factor. (b) The large circumference of the ring makes the apparatus available for investigating the effect upon sensitivity of varying the size of stimulus.

plane is 28 cm. long. The arm is graduated from 18° to 57° along the section that lies in the plane of the background and from 57° to 92° along the section at right angles. The graduations are based on the arc of a circle of 25 cm. radius. The arm is also split lengthwise to form two narrow arms, each 1 cm. wide, so separated that there is an opening (J) 0.8 cm. in width between them to admit the shank of the motor for rotating the discs needed to match the peripheral sensation. The opening to admit the shank of the motor may be clearly seen in all the pictures of the campimeter. The motor is shown at K on the right of Figure 1 and more clearly on the left of Figure 3. It has a shank 4 cm. long and 0.3 cm. in diameter, which can readily be thrust through the opening (J). The weight of the motor is so great that it can not be clamped to the arm (I-I') and thus be shifted with the arm as the retina is tested in different meridians. It has then to be supported so that it can readily and quickly be moved to any point in any meridian to which the arm (I-I') may be rotated. This is accomplished by the use of two rods—one vertical (L) and the other horizontal (M). The vertical rod (L) may be clamped to the table or other support on either side of the campimeter, and M is clamped to L. The vertical adjustment for any setting of the motor can thus be made along L and the horizontal adjustment along M. Holes are punched in each of the eight arms at six or more places to allow the insertion of small metal fasteners to hold the background screen to the frame. The stimulus frame may be seen at E. It is 20 cm. square and carries a groove for the insertion of the stimulus card. The stimulus card may be made of whatever colored paper the experimenter desires to use.

Figure 2 shows the front view of the campimeter in readiness for use; and Figure 3, the back view. A cardboard background has been fastened to the steel arms by means of paper-fasteners. Since the background is fastened to the arms attached to the brass collar (H), a circular gap is left at its center. This gap is filled by a disc (N), shown in Figure 3, which has been fastened to the arms just outside of the collar (H). The disc is 27 cm. in diameter and contains the stimulus-opening (O), the size

of which may be varied to accord with the purpose of the investigation. In the experiments reported in this paper, it was 15 mm. in diameter throughout. In order to complete the graduations on the fixation-arm to the stimulus-opening, disc (N) is graduated from 0° to 18° . A background 40 cm. in height is fastened to the extension arm (I). In the picture a paper screen made of No. 7 of the Hering series of grays has been attached by thumb tacks to the cardboard background. A strip of paper of the same quality as the background is placed along the opening (J), and the graduations from 0° to 92° are pricked on this strip as indicated by the markings on the back of disc (N) and arm (I-I'). These constitute the fixation-points. The card in the stimulus frame (E) is seen through opening (O). A disc (P) composed of black and white sectors has been placed on the motor (K).

The method of using the apparatus is as follows: The observer is seated in front of the campimeter screen with his head held in a rigid position by means of a mouthboard bearing the impression of the teeth in sealing wax. Since the graduations of the fixation-arm are based on the arc of a circle of 25 cm. radius, the distance of the eye from the stimulus-opening is chosen as 25 cm. The position of the eye in the observing plane may be obtained according to the method described by Fernald.¹² In order to facilitate excentric fixation in the nasal and temporal meridians, the head should be turned 45° nasalwards or temporalwards, as the case may be. With the head so placed, the eye can swing easily from the stimulus-opening to a fixation-point whose excentricity exceeds 90° . The unused eye is closed and covered by a bandage. The arm (I-I') is placed in the meridian desired, the position being indicated by the graduations on the collar (H). The experimenter covers the stimulus in the stimulus frame with a card, which we shall call the preëxposure card, while the observer takes the fixation required. At a signal given by the observer, the preëxposure card is withdrawn, the stimulus is exposed for three seconds, and the preëxposure card is replaced

¹² Fernald, G. M. The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. Psychol. Rev., Monograph Supplements, 1909, X., p. 18.

over the stimulus. The observer is required to rest the eye after each observation. Further provisions against fatigue are made by periods of rest after each fifteen minutes of observation.

When it is desired to measure the stimulus as seen in the peripheral retina in terms of brightness- and color-values of the central retina, the motor shown at K in Figures 1 and 3 is used. The method of making the measurement is as follows: If a direct vision judgment, for example, of the appearance of yellow at 25° in the temporal meridian is wanted, the cord (R) carrying a movable fixation-point, seen in Figure 2, is fastened in front of the 25° point on the graduated background. The observer, in position, fixates the 25° point and brings the movable point in line with the eye and the 25° point. This point then serves as the new fixation-point, and the graduated strip covering the opening (J) is removed. The required discs are placed on the motor immediately behind the new fixation-point, and their proportions are changed until the observer judges that the sensation aroused in the periphery is matched by that aroused in the center by the measuring-disc on the motor. In making this judgment, the method of ascending and descending series was used.

In this investigation, stimuli of blue, yellow, red, and green pigment papers of the Hering series were employed. White, black, and gray papers of the Hering series served to make the backgrounds. Results were obtained from three observers: Miss Campbell, C, graduate student in Bryn Mawr College, who had no knowledge of the problem in hand, Dr. Ferre, B, and the writer, A.

C. DETERMINATION OF THE BRIGHTNESS OF THE COLORED STIMULI EMPLOYED IN THE INVESTIGATION.

At every turn in our problem, it was necessary to know the black-white-values of the colored papers that formed our stimuli, as they appeared in the central and peripheral retina at full and decreased illumination. It was thought best, therefore, to devote a separate chapter of our report to a discussion of the methods used in determining these values. The method of flicker photometry was used throughout except at the limit of peripheral color vision, where it was possible to use the method of direct com-

parison. The black-white-values of the colors were determined for the central retina by means of the Schenck *Flimmer Photometer*. As this apparatus is not adapted to indirect vision work, it was necessary to devise a means by which the brightness of the stimuli at any point in the peripheral retina could be determined by the flicker method. The conditions of our experiment made it essential that these determinations be made not only in terms of black-white-value but also of colorless pigment paper, the brightness of which would approximately be the same as that of the colored stimulus. In order to make the latter determination possible, a series of gray papers varying in brightness by very small amounts was required. The Hering papers, ranging in number from 1 to 50, were found to furnish a series which varied in brightness by amounts sufficiently small to serve our purpose.

The use of the flicker method in photometry is based on the fact that two surfaces are considered equal in brightness when upon their alternation one with the other at a certain favorable rate of speed, no experience of flicker results. Obviously a very important point in the method is to determine what this rate of alternation should be. It should be determined empirically for each observer in a preliminary experiment. To make the determination we must be able to produce known brightness differences in different parts of the scale and to try the effect on flicker of different rates of speed for these brightness differences. This can be accomplished by making the preliminary experiment with colorless surfaces, for very small differences in brightness between two colorless surfaces can be estimated by the method of direct comparison. (This could not be done if one or both of the surfaces were colored.) Working then with colorless surfaces by the aid of the method of direct comparison, not only do we know at every stage of the experiment how much brightness difference is produced, but we standardize the flicker determination in terms of the method of direct comparison to which all indirect methods of determining brightness equality must conform if their results are to be of any value. In making our preliminary determination, then, colorless surfaces should be used and that rate of alternation, equal to or in excess of the

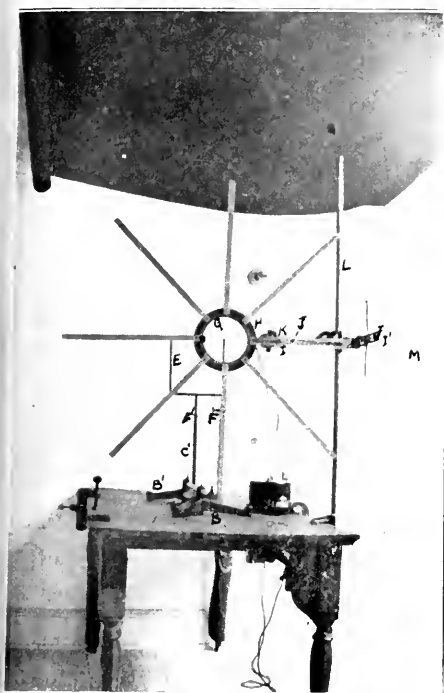


FIGURE I

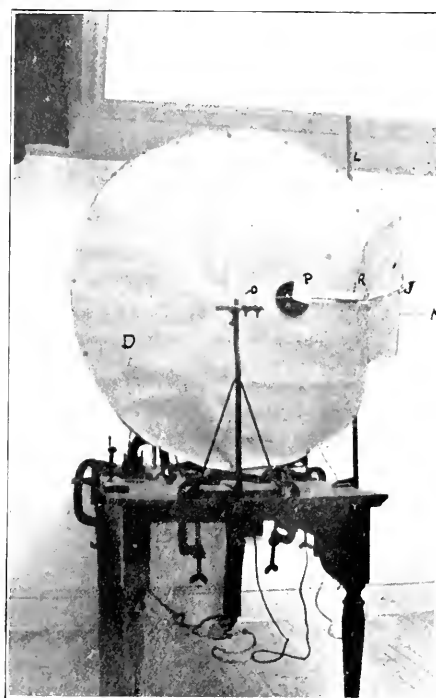


FIGURE II

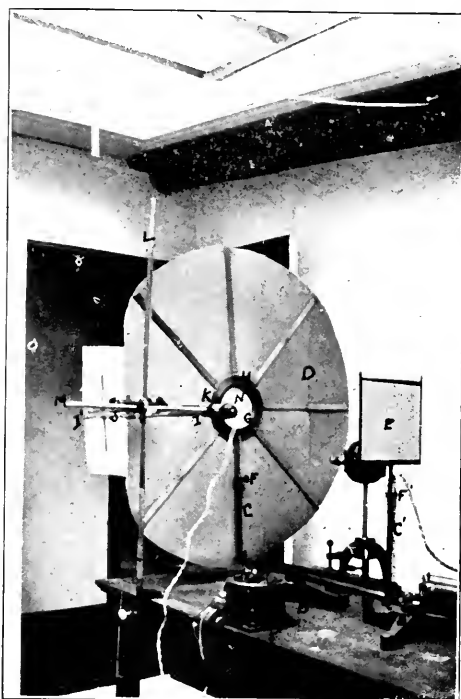


FIGURE III

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fusion rate for the color in question, should be selected at which the smallest difference in brightness between the two surfaces produces flicker. This speed may be considered as giving the maximum sensitivity to the method for the given observer and may be used for that observer in the color work. Applying this method to the determination of the brightness of a colored paper, we may consider that a colored and a gray paper are of equal brightness when no flicker is produced by the rotation of equal sectors of each at the chosen rate of speed. In order to prevent induction from the surrounding field, the rotating disc should be viewed through an opening in a screen of the same brightness-value as the disc itself. This requires that the gray sector, the colored sector, and the screen all be of equal brightness-value. The final value of this brightness must, however, be reached by a series of approximations. That is, the gray sector and the screen must at each trial be chosen of the same brightness, and both must be changed alike until a gray is finally obtained which does not produce flicker when it is rotated with the colored sector at the chosen rate of speed. Owing to the great number of steps in the series of approximations needed to reach the gray-value of the color, it was impracticable to change the large campimeter screen at each step. Moreover, to prevent brightness induction over the stimulus, it was not necessary to have so large a part of the surrounding field, as was comprised in the entire screen, of the same brightness as the stimulus. Squares 30 cm. on a side were found to be quite adequate for the purpose and to have the practical advantage that they could be quickly and easily changed. Since the sensitivity of the retina to flicker varies from point to point as we pass from the fovea outwards, it is found to be important that the opening in the screen be made small so that the area of the retina stimulated shall be uniformly sensitive to flicker. And, further, since the area of the retina influenced by a given stimulus decreases as we pass from the fovea to the periphery, because of decrease in the visual angle, it is necessary that the stimulus-opening be proportionately increased in the peripheral observations, in order to maintain the size of the stimulated area of the retina constant. Both of these conditions were met sufficiently accurately for our purpose, by using two

openings of different size, the smaller to be employed at all points from the fovea to 20° peripheralwards, and the larger to be used from the 20° point to the extreme periphery.

The method used to determine the brightness in terms of gray paper of a given color in central vision was as follows. From the series of squares of gray papers having the smaller of the two sizes of stimulus-openings (3 mm. x 1 mm.) one was selected which was judged by the method of direct comparison roughly to approximate the brightness of the color in question. This square was fastened upon the campimeter screen so that the stimulus-opening passed vertically through the center of the opening in the original screen. A disc compounded of 180° of the given color and 180° of the gray of the brightness of the square, was rotated behind the stimulus-opening and the observation made for flicker. Lighter and darker grays were in turn substituted in disc and screen and the observation was repeated. The gray which produced no flicker at the chosen rate of speed is, in terms of the method, the gray of the brightness of the color. The determinations were not at all difficult nor uncertain. Flicker was readily discernible in the gray lighter and darker than the one which was chosen, at the speed of rotation at which the one chosen showed no flicker. Our determinations showed that at the standard illumination¹³ used throughout the work, the method of obtaining which will be discussed later, the brightness of Hering blue for central vision equalled that of Hering gray No. 41; of red equalled gray No. 24; of green equalled gray No. 8; and of yellow equalled gray No. 2. These values were the same for all of our observers.

For the determination of the brightness of the colored stimuli in peripheral vision, the same method was used with the exception that at points in the periphery beyond 20° , the screens having the large stimulus-openings, 15 mm. in diameter, were used. The results of the peripheral experiments differed from the central at standard illumination only in case of blue. Blue was found to lighten in the periphery so much that gray No. 21 was determined

¹³ Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles.

by one observer to equal it in brightness. The determinations at the peripheral limit of sensitivity to color were made by the method of direct comparison. On the campimeter was mounted a gray screen for each of the colors in turn the brightness of which was such that when the stimulus was observed beyond the limits of color sensitivity, the color in each case changed into the gray of the brightness of the screen. If a gray lighter or darker was used, the stimulus appeared either darker or lighter than the screen.

The black-white-values of the colors for peripheral vision can not be determined directly because for the direct determination the Schenck *Flimmer Photometer* with its graduated sectors of black and white or some similar device must be used. This photometer is not adapted for peripheral vision work. A determination, then, had to be made with the photometer in the central retina for the grays which had been found by the method described in the preceding paragraph to equal the colors in brightness in the peripheral retina.

In one section of the investigation, it was found necessary to work at decreased illumination, and to know the brightness of the colored stimuli under these conditions. The decreased illumination was obtained by drawing the black curtains, until the illumination was slightly less than that of a cloudy afternoon.¹⁴ The colors appeared a little less saturated, and slightly altered in color tone. The green was a trifle bluish, the yellow was changed toward orange, and the blue appeared slightly reddish. Determinations were made at this illumination according to the method described above, of the brightness of the colors in central and in peripheral retina. The results are stated in Tables I and II. The first column shows the white-black-values of the stimuli at standard illumination in central vision; the second shows the same values in terms of the Hering gray papers; the third represents the brightness-values in peripheral vision at the limit of sensitivity; and the fourth and fifth columns show the brightness of each stimulus at the center and at the periphery under conditions of decreased illumination.

¹⁴ Measured in foot-candles by means of the Sharpe-Millar portable photometer, this decreased illumination equalled 1.65 foot-candles.

Table I records the results of Observer *A*; Table II those of Observer *C*.

TABLE I.

A. Showing the brightness-values of the Hering principal colors at standard and decreased illumination.

Stimulus	Brightness at Standard Illumination			Brightness at Decreased Illumination	
	At center		At limit of sensitivity in periphery	At center	At limit of sensitivity in periphery
Yellow	white 236° black 124°	gray no. 2	gray no. 2	gray no. 2	gray no. 3
Green	white 100° black 260°	gray no. 8	gray no. 8	gray no. 8	gray no. 5
Red	white 41° black 319°	gray no. 24	gray no. 24	gray no. 24	gray no. 50
Blue	white 15° black 345°	gray no. 41	gray no. 28	gray no. 35	gray no. 13

TABLE II.
Observer C.

Yellow	white 236° black 124°	gray no. 2.	gray no. 2	gray no. 2	gray no. 3
Green	white 100° black 260°	gray no. 8	gray no. 7	gray no. 7	gray no. 4
Red	white 41° black 319°	gray no. 24	gray no. 24	gray no. 24	gray no. 50
Blue	white 15° black 345°	gray no. 41	gray no. 21	gray no. 35	gray no. 7

Whether or not the peripheral retina functions differently from the central retina and must, therefore, be assumed to possess a different sensory mechanism, is a question of considerable importance to theories of color vision. Upon this question the results shown in Tables I and II have a direct systematic bearing. But since the comparative functioning of central and peripheral retina will be made the subject of a later report of work already completed by the writer, the significance of these results need not detain us here. We need only note in passing,

that the brightness changes that occur when a stimulus is carried from central to peripheral vision are similar to those that obtain in central vision when the illumination is decreased. With regard to this point our tables show (*a*) that in the peripheral retina at standard illumination, the colors have very nearly the same brightness relations that they have in the center at the decreased illumination we used; and (*b*) that the brightness relations of the colors seen in the peripheral retina at decreased illumination approximate those of the colors in the center when the illumination is further decreased. These latter changes known as the Purkinje phenomenon are in the following directions: blue and green relatively lighten; red and yellow relatively darken.

In Tables I and II, showing the comparative brightnesses of the color sensations at center and periphery, the lightening of blue and green and the darkening of red in the periphery are sufficiently pronounced to need no comment. But measured by these results, the change in yellow seems to be insignificant. If, however, yellow is observed in the periphery at decreased illumination and is compared with gray No. 2, that is, the brightness of yellow both in center and periphery at standard illumination and in center at decreased, it appears to be much darker than the gray screen. Contrast from the screen exaggerates this darkening to some extent but the change in the brightness of the sensation due to peripheral stimulation alone is considerable.

D. THE FACTORS INVESTIGATED.

The factors we have investigated with regard to their influence upon the color observation are: (1) the brightness of the stimulus; (2) the brightness of the field surrounding the stimulus; (3) the brightness of the preëxposure; and (4) the general illumination of the retina.

1. *Brightness of the Stimulus.*

It will be remembered from the historical discussion (p. 45 ff.) that the four men,—Bull, Hegg, Hess, and Baird,—who recognized the need of equating the intensity of colored stimuli for a determination of the relative limits of color sensitivity, equated them also in brightness. They apparently assumed the need of

this equation without having investigated the influence of the brightness difference between the colors upon the breadth of the color zones. As a result of a careful investigation of this question, we are able to show that not only is no advantage gained by equating the brightness of colors when determining their limits of sensitivity, but a positive disadvantage is suffered. The following reasons may be cited in support of the latter statement. (a) The quality of certain colors is changed when their brightness is altered. This disadvantage, first mentioned by Chodin, was a source of great difficulty to Hegg, as we have seen (p. 74).¹⁵ (b) Colored stimuli which have been equated in brightness are necessarily reduced in intensity. For this reason, no true nor comprehensive estimate of the color sensitivity of the retina can be obtained with stimuli equated in brightness. (c) The technique involved is extremely cumbersome.

Our investigation of the influence which the brightness difference between the four principal colors exerts upon their limits covers four points. (a) The work on the first took its start from Hegg.¹⁶ Hegg apparently assumed that the difference in the brightness of the four colors,—red, green, blue, and yellow,—at full saturation is sufficient to affect their limits, and, therefore, that they must be equated in brightness before a determination of their relative limits is made possible. With the view of testing the validity of this assumption, we sought to ascertain whether a brightness change in any one of the four colors, equal to the maximal brightness alteration made in Hegg's equation, affects the limits of sensitivity to that color, provided the alteration is produced without changing the amount of colored light coming to the eye. The test was made doubly strict by varying the colors both toward white and toward black, thus covering a variation whose range was twice as great as was required. That is, both white and black in turn were added to each of the colors in

¹⁵ Mrs. Franklin remarks concerning Hegg's oil papers: "Of the 'normal' colors prepared by Hegg, the red and the yellow would not strike the plain man as at all deserving of the name" (*Psychol. Rev.*, 1897, IV., p. 96).

¹⁶ A start was taken from Hegg, in preference to the other three investigators, because he is the only one who gives adequate numerical data concerning the extent of brightness alteration he made in obtaining this equation.

amounts equal to Hegg's maximal change, and the limits of the stimuli thus obtained were compared with each other, and with the limit of a stimulus equal to them in physical intensity and to the original color in brightness. No effect whatever on the limits was found as a result of these brightness alterations. (b) We next sought to ascertain whether a brightness equation is necessary when working with the standard pigment papers of the Hering series. A determination of the maximal brightness difference between the colors was made at the limit of sensitivity to each, and the above experiments were repeated using the maximal value obtained in these determinations, as the amount of variation. In no case were the limits affected. (c) Following Hegg's plan of equating the four colors to one of mid-brightness, we next determined the maximal amount of change required to equate the standard Hering colors to the brightness of green. Since the amount of change was obviously much less than the variations used in (b), it was not necessary to repeat the experiments on the limits of sensitivity with this amount of variation. In two ways, then, we shall have shown that it is unnecessary to equate the Hering colors for brightness when determining their relative limits of sensitivity, since neither the maximal amount of change required to bring them all to a medium brightness, nor the maximal amount of brightness difference between the colors, has any effect upon the color limit when this change is applied as a variant in the direction of either white or black, provided that the amount of colored light coming to the eye remains unaltered throughout. These results may seem contradictory to the statement made by certain other writers and by ourselves¹⁷ that dark colors appear more saturated than light colors of equal physical intensity, that is, white exerts a greater inhibitive action than black upon color. This brings us to our fourth point. (d) We have to explain why these brightness changes which are known in general to affect the sensitivity of

¹⁷ Ferree, C. E. and Rand, G. Colored After-image and Contrast Sensations from Stimuli in Which No Color Is Sensed. *Psychol. Rev.*, 1912, XIX., pp. 215; An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. *Journ. of Philos. Psychol. and Scientific Methods*, 1911, VIII., pp. 294-297.

the retina to color do not change the limits of color. The explanation, as will be shown on p. 104, is found in the extreme rapidity with which color sensitivity of the retina falls off near the limits. The amounts of brightness dealt with in the above cases do not produce a sufficient change in the saturations of the light and the dark color to cause their limits to differ by even 1° , because the stimuli reduced in intensity by this amount of brightness are still sufficiently intensive to cause the color limits to occur within the zone of rapid decrease in sensitivity. If the stimuli had given a very small amount of colored light to the eye, and the limit of sensitivity had consequently occurred nearer the center of the retina where the sensitivity falls off more gradually, the difference in saturation between a dark and a light color of equal physical intensity, might have been sufficient to cause the latter to have a narrower extent of visibility. But since the amount of intensity at which this exception occurs is much less than is ever likely to be used in investigating the color limits, the exception can scarcely be entitled to more than theoretical consideration. The writer regrets to report that she has not carried on this investigation with spectral light. While she has no reason for believing that the results would in general be different, still for the sake of knowing the exact values of the brightness quantities obtaining in case of spectral colors, she hopes to make the investigation in the near future.

To investigate these points, it was necessary to devise a method whereby the brightness of the color can be altered without changing the amount of colored light coming to the eye. When one is working with pigment papers, the brightness of the stimuli can easily be varied without changing the intensity of the stimulus. For example, discs can be compounded of 260° of yellow and 100° of white, 260° of yellow and 100° of black, 260° of yellow and 100° of the gray of the brightness of yellow. In these cases we have, in order, a tint of yellow, a shade of yellow, and a yellow reduced in saturation but not changed in brightness, —all giving the same amount of yellow light to the eye. If it should be desired to make the tints darker and the shades lighter, the brightness sectors can be chosen of white or black in any proportion that is required.

In determining the size of the brightness sector to be used for the first point in this investigation, we are obliged to proceed largely by inference from Hegg's rather meager report of his work. He had equated the peripheral brightness-values of his four stimuli to green. In doing this, 84° of white and 5° of black were added to red. No statement whatever is made by him with regard to the amount of white and black added to blue and yellow. These amounts have, therefore, to be inferred. In doing so, care was taken to make the amount sufficiently large to give our test due rigor. We have mentioned that blue lightens in the periphery until its brightness is much like that of red. For Observer *A* it is slightly darker than red, for *C* slightly lighter. It is fair, then, to assume that 100° represents the maximal brightness difference that Hegg found to obtain between the colors in their peripheral values. Observations were taken from sets of discs composed of sectors of 260° of each of the four principal colors and 100° in turn of white, of black, and of the gray of the brightness of the color. The surrounding field and preëxposure in each case were of the gray into which the stimulus color changed at the limit of sensitivity. Several observers were used and several meridians explored, but in no case could a difference in the limits of sensitivity be detected for the color mixed with white for the color mixed with black, and for the color mixed with the gray of the brightness of the color. Space will not be taken here to record the results for all observers in all meridians investigated. The results obtained for Observer *A* for the temporal and nasal meridians are selected as typical. They are shown in Table III.

We have seen that the alteration made by Hegg in his brightness equations, when applied to stimuli of Hering standard papers, does not affect their limits of sensitivity. We now pass to our second point, namely, whether the full brightness difference in these colored papers should be considered as in any way affecting their limits. This is somewhat different from the preceding point in which we were concerned merely to find out whether Hegg's attempt to reduce all the colors to a mid-brightness could be considered as having any effect upon their limits.

TABLE III.

A. *Showing the limits of sensitivity¹⁸ when the colors are mixed in turn with 100° of gray of the brightness of color, 100° of white, and 100° of black without altering the amount of colored light coming to the eye.*

Stimulus	Meridian	Limit of stimulus when mixed with 100° gray	Limit of stimulus when mixed with 100° white	Limit of stimulus when mixed with 100° black
Yellow	Temporal	42°	42°	42°
Green		35°	35°	35°
Red		41°	41°	41°
Blue		51°	51°	51°
Yellow	Nasal	88°	88°	88°
Green		59°	59°	59°
Red		85°	85°	85°
Blue		91°	91°	91°

We wish here to find out whether the actual difference in brightness between the extreme members of the series, blue and yellow, affects the limits of any one of the series. To do this, our method was to determine the difference between blue and yellow at their limits of sensitivity, to vary each color toward both white and black by the amount of this difference, and to find out whether the limits of the light and the dark stimulus differ from each other or from that of a stimulus of equal intensity which has retained the original brightness of the color. This amount of variation was greater than was needed in case of red and green, because they do not differ from any member of the series by so great an amount. We have used this maximal amount, however, because we have not wished to leave room for any question as to the rigor of our test.

In order to ascertain the difference between the white-values of the colors seen in the extreme periphery, the Hering gray that represented the peripheral brightness of each stimulus as determined by the method of direct comparison at the limit of sensitivity (see Tables I and II), was mounted on the Schenck

¹⁸ The point at which color loses all trace of its original quality is recorded as the limit of sensitivity.

Flimmer Photometer, and its white-value determined. For Observer *A*, blue was the darkest color. Its brightness was equal to white 37° , black 323° ; that of red was equal to white 41° , black 319° ; that of green was equal to white 100° , black 260° ; that of yellow, the lightest color, was equal to white 236° , black 124° . The maximal brightness difference, then, was between blue and yellow, and was equal to 199° . To ascertain whether this brightness difference is sufficiently great to influence the breadth of the color zones, the limits of stimuli composed of 161° of each color and 199° of black, and of 161° of color and 199° of white were compared with each other and with the limit of a stimulus composed of 161° of color and 199° of gray of the brightness of the color. The first two stimuli, it will be observed, were composed of the color altered in brightness toward black and toward white by an amount equal to the difference in white-value between blue and yellow; the third stimulus retained the original brightness of the color while it sent the same amount of colored light to the eye as the other two. In every case, on either the nasal or the temporal meridian, the limit of color visibility was the same whether the stimulus was the color in its original brightness or whether its brightness was changed in either direction, toward black or toward white, by an amount equal to the maximal difference between the white-values of the colors as seen in peripheral vision.

As we have said, our test is unnecessarily severe. Not only have we lightened blue and darkened yellow by an amount equal to the difference in their white-values, but we have also darkened blue and lightened yellow by the same amount. If a brightness equation were found to be necessary, the variation would by no means be as wide as the one we have made. It would be necessary merely to darken some colors and to lighten others to a medium brightness.¹⁹ We feel confident then in stating the following

¹⁹ The change we have made in one direction is no greater than had to be made by Baird who equated all of his colors to the brightness of blue. Baird, it will be remembered, was forced to employ this brightness as standard because his equation of brightness was made by interposing an episcotister between the stimulus and the eye of the observer. This method permitted change only in one direction, towards black. The defects of his method

two points:—(a) The amount of change required to equate in brightness the colors, red, green, blue, and yellow, has no effect upon their color limits and the precaution of equating is, therefore, superfluous. (b) The actual brightness difference in the colors at standard saturation has no effect upon their relative limits.

While we have shown that variations of brightness in the above amounts do not affect the limits when there is no alteration in intensity of the colored light, we do not claim that there might not be a change sufficiently large to influence the limits. This would be a broader thesis than we wish to maintain. We have merely been concerned with showing that brightness alterations as great as the difference between the white-values of the Hering standard papers do not affect the limits. Strictly speaking, this is as far as our criticism of previous attempts to standardize brightness need carry us. But it is a matter of fact that a color mixed with black gives us a sensation that is more intensive than that produced by a color of equal physical intensity which is mixed with white, and that the limen of color is much lower when the color is mixed with black than when mixed with white. Brightness change, then, does affect the retina's sensitivity to color, and, within limits, the breadth of the zones of sensitivity. We have, therefore, extended our investigation to explain why changes of the order given above do not affect the color limits, and to determine roughly to what extent brightness change may be made without affecting them. As already indicated we must look for the explanation of our results to the rapidity with which the sensitivity of the retina falls off from point to point from center to periphery. If, for example, it be found that sensitivity falls off gradually from the fovea to near the limits (as determined with stimuli of full intensity,) and from that point on, it falls off abruptly, we might expect that light and dark colors of equal physical intensity will have different limits up to the point on the retina at which the abrupt have already been pointed out. With a spectroscopic mixer as the ideal apparatus for investigations with the light of the spectrum, the brightness changes can be readily made in both directions, as they can with pigment stimuli.

change in sensitivity begins, and the same limits from that point on. It is obvious that in either case, whether or not there is a difference in limit, depends upon whether the difference in the inhibitive action of white and black upon the color is equal to the amount of change of intensity required to affect the limit. If sensitivity falls off gradually, a relatively small change in intensity is sufficient to widen the limit, and, if abruptly, a relatively large amount of change is required.

By way of explanation, it is our purpose to show (*a*) that the sensitivity of the retina falls off gradually to a point within 5° of the limit and from that point to the limit, it falls off very abruptly; (*b*) that the white and black sectors added to the colored stimuli in the foregoing tests did not weaken the stimuli sufficiently to narrow their limits more than 3° ; and (*c*) that within the zone 3° from the limit, the difference between the apparent saturations of our light and dark stimuli was not sufficient to affect their limits.

An inspection of the results given in Table VIII and discussed in the next section (p. 117 ff.) will show the rate at which the sensitivity of the retina falls off from the fovea to the periphery and will establish our first point. The decrease is gradual from the center to within 5° of the limit, beyond which point it grows progressively more abrupt, becoming extremely abrupt from a point 3° from the limit to the limit. For example, when the screen and preëxposure of the gray of the brightness of color are used, the limen of yellow at the fovea is 18° ; at 39° from the fovea in the temporal meridian, that is, 5° from the limit of yellow, it is 100° . Thus over a space of 39° , the limen has increased only 82° , and average of little more than 2° of increase per degree of retina traversed. At 41° , however, it has reached a value of 150° , an average of 34° of increase per degree of retina traversed; at 42° , a value of 240° , an average of 90° of increase per degree of retina traversed; at 43° , a value of 330° , an average also of 90° per degree of retina traversed. With regard to the second point, it will be remembered that the extreme amount of white or black we added to our colors was 199° . This left 161° of color in the stimulus discs. Table VIII

(page 119) which gives the values of the color limens at different points near the limit, shows that this amount of color is above the limen for each color at 3° from the limit. In our tests, then, we were working well within the 5° limit bounding the zone of abrupt decrease in sensitivity, as our explanation required us to show. With regard to the third point, it will be seen from the same table that, when working at the point 3° within the limit, in order to extend the limit 1° , an increase of the colored sector by amounts ranging from 65° in the case of blue to 115° in the case of green, is required. It scarcely need be pointed out that the apparent saturation of a stimulus composed of 161° of color and 199° of black is not greater than the apparent saturation of a stimulus composed of 161° of color and 199° of white by an amount equivalent to from 65° to 115° of color.

Having explained why brightness differences equal to those found in red, green, blue, and yellow papers of standard saturation have no effect upon the limits of color sensitivity, we turn next to a determination of the range within which brightness change may be made without affecting the limits of sensitivity. Two ways occur to us by means of which a rough estimate of this range may be obtained. (a) Stimulus colors at full saturation may be used and the brightness excitation be added as after-image or contrast or both. In this way the amount of colored light coming to the eye is not altered by the brightness added, that is, the physical intensity of the color in the stimulus is not affected. If we wish to use the contrast and after-image effects, the card which covers the stimulus before exposure can be adjusted so that an intensive after-image is superimposed upon the stimulus when the card is removed. By a proper regulation of this card and of the campimeter screen, which causes contrast induction across the stimulus, varying amounts of white and black can be added to the stimulus, care being taken to measure these amounts and to keep them equal, each to each. Since, according to our measurements in this region of the retina, the after-image and the contrast excitations from white are more intensive than those from black, the quality of the screen and

preexposure designed to give dark contrast must be regulated until the brightness excitation aroused is found to be equal in amount to the white given by the black screen and preexposure. A series of these changes can be made until a point is reached where the sensations are reduced in intensity sufficiently to allow the more saturated dark color to be seen farther out than the light color. The sum, then, of the amounts of white and black added in turn to the stimulus, will give the range of brightness change that may be made in a stimulus of full intensity without causing the difference in brightness to be a factor influencing color limits. (b) Equal sectors of white and black may be added to the stimulus color until a point is reached where the darkened color is seen farther out than the lightened. This method has the disadvantage that with each addition to the brightness sector, there is a corresponding subtraction from the color sector. On the other hand, however, it may have a possible advantage over the former method in that the brightness excitation that is added to the color is aroused by light-waves, as is the case with the standard colors whose brightness differences gave rise to our problem; hence any theoretical questioning is obviated as to the quantitative equivalence of the action of a brightness excitation objectively aroused to an excitation aroused as after-image or contrast. But since we can not work with colors at full saturation, the disadvantage is probably much in excess of the advantage. We can doubtless come much closer to the value we are seeking by the first method. As the work by this method is not completed, its report will be deferred until a later paper. The results obtained by the second method are given in Table IV. In this table we have shown how much the colored sector may be reduced by the addition of black and white, without changing the limits for the darkened and the lightened color. If a further reduction is made, the darkened color will be seen at a greater excentricity than the lightened color. The results show that 240° of black, white, or gray of the brightness of color may be added to yellow and the limits for the three shades of color so formed will still coincide; 225° to red; 215° to blue; and 230° to green. Since, roughly speaking, the amount of inhibition will be inversely proportional to the amount of color

present, it is obvious that if the colors could have been maintained at full intensity, as they usually are in the investigation of sensitivity, a still greater brightness change would have been possible. While we may not have determined by this method just how much brightness difference there may be between colors at full saturation without affecting the limits, we have shown beyond doubt that there may be much more than is found between the standard pigment colors.

Table IV gives some of the results of this investigation for Observer *A* in the temporal meridian. Each observation was taken with screen and preëxposure card of a gray of the brightness of the color. Since the results in the nasal meridians are very similar to these, space will not be taken to report them. As the sensitivity of the retina falls off gradually in all directions until within 5° of the limit, the limen at this 5° point is almost identical, whatever the meridian.

TABLE IV.

A. Showing how much white, black or gray of the brightness of the color we may add to a colored stimulus and still have a coincidence of limits for the three shades of color, providing the amount of colored light coming to the eye is kept constant.

Stimulus	Value of colored sector	Value of brightness sector (gray of brightness of color, white, or black)	Limit of sensitivity when color is mixed with gray of brightness of color	Limit of sensitivity when color is mixed with black	Limit of sensitivity when color is mixed with white
Yellow	260°	100°	42°	42°	42°
	180°	180°	40°	40°	40°
	90°	270°	37°	38°	37°
	120°	240°	40°	40°	40°
	105°	255°	39°	40°	39°
Green	120°	240°	30°	31°	30°
	130°	230°	31°	31°	31°
Red	120°	240°	37°	38°	35°
	135°	225°	39°	39°	39°
Blue	135°	225°	48°	48°	43° ²⁰
	145°	215°	49°	49°	49°

²⁰ The decided narrowing of the limit of the blue stimulus in this case

But there is more than one kind of problem which deals with peripheral color sensitivity. To avoid any possible misunderstanding of our position, a word may be added to show when it is of advantage and when of disadvantage to equate stimuli in brightness. (a) When investigating the limits of color sensitivity and when the brightness of the surrounding field is the same as the brightness of the stimulus color, a brightness equation of the different colors, within the limits we have just determined, is not only unnecessary, but a positive harm. This, moreover, is the proper regulation of the brightness of the surrounding field for all investigations of the relative and absolute limits of sensitivity and of the limens of color at different points on the retina. (b) When, however, the brightness of the surrounding field is different from that of the color, the factor of the induction of the screen must be taken into account. Since brightness contrast follows the law that maximal contrast occurs when there is a maximal brightness opposition, different amounts of contrast will be induced across colors of different brightnesses. But under these conditions, only one legitimate problem can arise, namely, to test the effect of the screen. There are two points to this problem. (i) Knowledge of the effect of different screens upon the same color may be desired. In this case, the problem of

is due to the following cause. For Observer *A* there is a small spot in the horizontal temporal region of the right eye that is totally insensitive to blue light. This miniature spot of blue-blindness extends from 43° to 47° in the horizontal temporal meridian. Now since the apparent intensity of the sensation aroused by the stimulus composed of 135° of blue and 235° of white was not sufficient to allow the color to be seen on the peripheral side of this blue-blind spot, its limit occurred on the foveal limit of the spot, at 43° . It may be added that spots of this type are not unusual. The writer has found in every eye she has tested one or more spots that are partially or totally insensitive to one color alone. Relative to these blind spots, the following interesting features may be noted. (a) Although totally blind to a given color, they have normal sensitivity to its complementary color. (b) They give a fully saturated complementary-colored after-image of this color to which they are blind. (c) They show the usual cancelling action between the color to which they are blind and its antagonistic color. In short, they seem to be exact replicas in the periphery of the normal eye of the unique type of color-blindness described by Schumann (see Schumann, F. Ein ungewöhnlicher Fall von Farbenblindheit. Bericht über die 1. und 2. Kongress für experimentelle Psychologie, 1904, pp. 10-13.

brightness equation would not arise. (ii) Knowledge of the effect of the same screen on different colors, or of the comparative effect of different screens on more than one color may be desired. In this case the colors may or may not be equated in brightness:—the question depending upon the requirements of the problem. If they are not equated in brightness, there will be different amounts of induction with each screen for each color. If they are, the colors will be altered in intensity and often in color tone. No general rule can be laid down as to equation or non-equation in these cases. Each has to be settled on its own merits and in accord with the requirements of the problem in hand. What we wish to emphasize more than anything else at this point is that, while at different times in color work, one may need to make legitimate use of a surrounding field which differs in brightness from the stimulus color, it should never be done in any investigation of the relative or absolute limits or limens of color sensitivity. The use of the perimeter and the dark-room is a notable instance of the violation of this precaution. The surrounding field of intensive blackness induces a different amount of white over each of the colors unless they are of the same brightness. And if they are equated in brightness, all the disadvantages which, as pointed out earlier in the paper, result from this equation, are suffered in the investigation. Moreover, to equate the stimuli in brightness is not to get rid of the induction of the surrounding field. We still have, after equating, a large amount of brightness induction which operates against a determination of absolute limits by tending to narrow the limits of sensitivity for all colors; and against a determination of relative limits by narrowing the different colors unequally, depending upon the difference in the inhibitive action of the same amount of white upon them.

2. *Brightness of the Field Surrounding the Stimulus.*

When a small color stimulus is surrounded by a large field of white or black, a sensation is given which consists of the color mixed with black or white, due to contrast induction from the surrounding field. The influence of the brightness of the surrounding field upon color sensitivity resolves itself, then, into the

question of the fusion of colored with colorless light sensation in central or peripheral vision, according to the part of the retina that is stimulated. The details of this fusion in central vision have been taken up by the writer working in collaboration with Dr. C. E. Ferree,²¹ in which work it was shown that the effect of fusing a colored sensation with white, black, or gray is twofold. (a) There is a quantitative effect due to the inhibition of chromatic excitation by achromatic. White inhibits color most, the grays in order from light to dark next, and black the least. The records of all the observers used in this investigation show that the achromatic series inhibits red and yellow considerably less than blue and green. (b) There is also a qualitative effect. The tone of certain colors is changed by the action of the achromatic excitation. The change is greatest when the stimuli are blue and yellow.²² Yellow, when mixed with black, gives a sensation of olive-green; and blue when mixed with white, black, or gray gives a sensation of reddish-blue.

As a factor influencing the limits and limens of the sensitivity of the retina to color, the inhibitive, or quantitative effect of the fusion concerns us more than the qualitative. As we have stated, a white surrounding field, for example, a white campimeter screen, induces black across the stimulus which fuses with and modifies the resulting sensation; while a black screen induces white. For an estimate of the amount of brightness contrast that is induced by white and black screens across yellow, green, red, and blue stimuli, the reader is referred to the section: *Quantitative Estimate of the Influence of the Change of Illumination upon the Induction of Brightness by the Surrounding Field* (p. 138). The question is considered in detail in that section rather than in the present one, because it will be necessary at that point to compare the amounts of brightness induced by the white and

²¹ Ferree and Rand. An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297. This is only a brief preliminary report of the work. A full report will be published later.

²² How far the qualitative effects of the fusion of colored with colorless light sensation in central vision are paralleled in peripheral vision, will form the discussion of a later chapter of this investigation, not reported in this paper.

black screens at standard and decreased illumination. In that section is shown also in what way the amounts of brightness induced by the screens were estimated, and within what limits the values obtained can be said to represent these amounts. Tables XII and XIII (pp. 142-143), columns 1, 2 and 3, give the amount of contrast that is induced by the white and black screens at standard illumination across the grays of the brightness of the colored stimuli at 25° and 40° in the horizontal temporal meridian for Observers *A* and *C*. The results of these tables may be summarized as follows:

1. The amount of induction from the white and black screens increases with the distance from the fovea.

2. The amount of induction from the white screen is greater than that from the black screen.²³

3. The white and black screens induce most across the stimuli that are farthest removed from them in brightness, and least across those which are nearest to them in brightness. That is, the white screen induces more black across the gray of the brightness of blue than across the gray of the brightness of yellow; the black screen induces more white across the gray of the brightness of yellow than across the gray of the brightness of blue.

The effect of this induction of the surrounding field may be shown by two methods: (*a*) by its effect on the limits of color sensitivity; and (*b*) by its effect upon the limens of color sensitivity.^{23a} Up to this time, so far as the writer knows, the effect of the surrounding field has been estimated only by the first of these two methods, by its effect on the color limits. This method, however, estimates the effect of the surrounding field upon the color sensitivity of the extreme peripheral retina alone. By the

²³ See footnote p. 141.

^{23a} Since sensitivity to color is measured by determining both the limen and j. n. d. of color, it might be thought that the effect of surrounding field could be measured in both of these ways. The determination of the j. n. d. would, however, show very little, because the induction of the surrounding field would affect both the standard and comparison surfaces. This will be true also of the effect of the brightness of the preëxposure, and of changes in the general illumination. In none of these cases has the writer considered it worth while to make the determination of the j. n. d.

second method, on the other hand, this effect can be measured in the central and paracentral regions, as well as in all parts of the peripheral retina. In order to make a complete study of the effect of the brightness of the surrounding field on color sensitivity, we have used both of these methods. The report of the work done by them is as follows:

a. The effect of the induction of the surrounding field upon the limit of color sensitivity.

Assuming that the law of brightness inhibition of color for the central retina holds for the peripheral retina, we should expect to find that, since colors have a lower limen in black than in gray or white, a white screen, which causes black induction across the stimulus, would be more advantageous to color vision than would a black screen, which causes white induction. Further, we should expect to find that a gray screen of the brightness of the stimulus, which causes no induction whatever, would be the most favorable.

An investigation of the color limits with screens of white, black, and gray of the brightness of the color, shows, however, the following facts:

1. Blue and green have widest limits with the gray screen, slightly narrower with the white, and narrowest with the black.
2. Red and yellow have widest limits with the black screen, slightly narrower with the gray, and narrowest with the white.

The color limits of Observers *A* and *C*, taken on the temporal and on the nasal meridian, are given in Table V and VI.

b. Explanation of the effect of the induction of the surrounding field on the limits of color sensitivity.

Turning to the explanation of these results, we shall here endeavor to account for the results obtained with the white and black screens. We have the following points to explain: (*a*) Blue and green have wider limits with the white screen than with the black, but the difference is comparatively small. According to the law of the action of white and black on colors, formulated from the results of work in the central retina, we should expect to find wider limits with the white screen, which induces black, than with the black screen, which induces white. Thus far, then, the results are in accord with the law, but the difference found

TABLE V.

A. Showing the limits of color sensitivity with screens of white, black and gray of the brightness of the color.

Stimulus	Limit with gray screen of the brightness of the color	Limit with white screen	Limit with black screen	Meridian
Yellow	44°	42°	45°	90° Temporal
Green	37°	36°	34°	
Red	43°	42°	44°	
Blue	53°	50°	49°	
Yellow	90°	88°	92°	90° Nasal
Green	64°	62°	60°	
Red	89°	87°	89°	
Blue	92°	92°	92°	

TABLE VI.

Observer C.

Yellow	49°	46°	50°	90° Temporal
Green	44°	42°	40°	
Red	45°	41°	45°	
Blue	56°	55°	53°	
Yellow	92°	92°	92°	90° Nasal
Green	87°	84°	53° ²⁴	
Red	92°	92°	92°	
Blue	92°	92°	92°	

between the inhibitive action of white and of black in the central retina would lead us to expect a greater effect on the limits. (b) Yellow and red have wider limits with the black screen than with the white. This is in direct contradiction to the law of fusion formulated for the central retina. With regard to explanation, two points must be considered. (1) The relative inhibitive action of black and white upon color must be investigated in peripheral vision; and (2) the rate of falling off in sensitivity of the peripheral retina must be ascertained.

²⁴ In this case, the qualitative change of green to blue caused the decided narrowing of the limit.

(1) *The relative inhibitive action of black and white upon color in peripheral vision.* The relative inhibitive action of white and black upon the colors must be investigated at all points from the fovea to the limits of sensitivity to see whether the law established for the central retina holds for all degrees of excentricity. If we find that the difference between their inhibitive actions lessens as we go towards the limits, we have a reason for the small widening of the zones of blue and green by the white screen. And if we find just within the limits of sensitivity for red and yellow that black inhibits these colors more than white does, we have a reason for the relative widening of the zones of sensitivity for these colors with the white screens, provided we can show that the effect of neither screen will carry the limits farther towards the fovea than the inner margin of this zone within which the exception is found.

To test the relative inhibitive power of black and white in the peripheral retina, the limen of color in black and white had to be determined. Two methods of procedure were possible with the apparatus used. By the first method, the stimulus was a disc with sectors of color and white or black which could be adjusted so that a liminal sensation of color was produced. In order to prevent brightness induction the screen had to be of a gray of the brightness of the stimulus used. With each addition of color to the stimulus, a change of the brightness was produced. The screen then had to be altered in brightness by an equal amount. Of the two methods of determining the brightness of the stimulus, described p. 91, the method of comparing the brightness of the colorless peripheral sensation with the surrounding field was obviously better adapted to the requirements of this observation than was the more cumbersome flicker method because the brightness of the stimulus was being continually altered. For the present case, the gray squares were used for surrounding field that had served a similar purpose for the determinations of the brightness of the stimuli in the periphery at standard and decreased illumination. The observer first made a preliminary judgment of just noticeable color, and then determined the gray that was equal in brightness to the stimulus. A square of this gray was then

mounted on the campimeter and the final determination of the limen was made. By the second method, the screens were removed and the skeleton apparatus alone was used. A disc composed of white and black sectors was placed on the motor so that it just filled the large circular ring at the center. This gave a surrounding field whose brightness could be adjusted at will. A small disc, 2 cm. in diameter, composed of sectors of the color to be investigated and black or white, was placed over the large black and white disc. The method of procedure was as follows. The observer took the required fixation, and observed the small disc to find the smallest amount of color that could be sensed when fused with white or with black, as the case happened to be. Before each determination, the experimenter adjusted the black and white sectors of the large disc, so that they equalled the brightness of the inner disc. This brightness was readily calculated from the following quantities:—the number of degrees in the colored sector, its black-white-value, and the number of degrees of white or black in the remainder of the disc.

Since the point in question was of considerable importance, both of these methods were used, the one as a check on the other. The first had the advantage of greater ease of manipulation and of employing a stimulus which was the same size as that used in the sensitivity experiments. The second had a possible advantage in the adjustment of the brightness of the surrounding field, but it was of disadvantage because the surrounding field could not be made so wide as by the former method and because a stimulus larger than that usually employed had to be used.

Results from both of these methods show the following facts: (1) As the fixation becomes more excentric, the difference in the inhibitive action of white and black decreases. (2) From center to periphery, the limens of green and blue are greater when mixed with white than when mixed with black; that is, the law of the greater inhibitive power of white holds for these colors in the periphery as well as in the center. (3) An exception to this law is found for yellow and red near the limits of sensitivity. From the center to within about 5° of the limit of sensitivity,²⁵ white

²⁵ By the limit of sensitivity is meant the widest limit of color determined at standard illumination.

has a greater inhibitive power than black over these two colors. But from this point to the limit, the reverse relation obtains, and red and yellow in this region have a greater limen in black than in white. How much this apparent exception to the law of fusion as it obtains in central vision is due to the natural darkening of red and yellow as they pass into the peripheral field of vision, we are not at this time prepared to state. Because of this darkening, there is more black fused with red and yellow than the results of Table VII express. These results represent the values of the colored and black sectors in the stimulus discs only and not the actual proportions of color and black excitations aroused.

Results are shown in detail in Table VII. They are taken from the records of Observer *A*, on the temporal meridian by the first method described. Column 1 indicates the stimulus used; column 2, the fixation at which the liminal determination was made, and columns 3 and 4, the limens of color mixed with white and black.

TABLE VII.

A. Showing the inhibitive action of white and black upon color in peripheral vision.

Stimulus	Fixation	Limen of color in white	Limen of color in black
Yellow	0°	40°	3°
	35°	85°	65°
	38°	95°	85°
	40°	120°	115°
	42°	290°	320°
Green	0°	45°	5°
	25°	80°	50°
	31°	130°	100°
	33°	200°	175°
Red	0°	30°	3°
	35°	80°	65°
	38°	120°	110°
	39°	135°	135°
	40°	155°	170°
	42°	290°	310°
Blue	0°	60°	10°
	35°	125°	65°
	41°	145°	140°
	42°	180°	170°
	51°	300°	280°

(2) *The rate of falling off in the sensitivity of the retina to*

color from center to periphery. To determine the falling off in sensitivity of the retina, the limen of color must be known at several points of excentricity. For this determination, the results given in Table VIII, which shows the limens of color when the brightness influence of the screen has been eliminated, best serve our purpose. They show that at 5° from the limit, the limen has been increased from three to tenfold as compared with the limen at 25° , or six to fourteenfold as compared with the limen at the center. The distance between the point 25° from the center, and the point 5° inwards from the limit averages for all colors about 10° . It is readily seen that the sensitivity falls off much faster from the point 25° from the center to 5° from the limit than it does from the center to the 25° point. At the point 3° inwards from the limit, the limen ranges from 145° of color, in the case of blue and green, to 150° of color, in the case of yellow and red. It is from this point that the sensitivity falls off with extreme rapidity. As was mentioned earlier in the discussion (see p. 105), a change in the fixation of 1° peripheralwards causes an increase in the limen of 65° or more, an increase that represents a greater lessening of sensitivity in 1° of excentricity than there was in the first 25° from the fovea.

Values of the limen for all colors with gray screens of the brightness of the color at 0° and 25° from the center, and 5° , 3° , 2° , and 1° from the limit are shown in Table VIII. They were determined in the temporal meridian of Observer A and are selected as typical. An equal zone of rapidly decreasing sensitivity was found on the nasal meridian also in every case where the limit of color sensitivity occurred within the range of our apparatus.

In Tables V and VI, it was shown that the limits of color are not changed more than 5° with the white and black screens from their values with screens of the brightness of the color used. The results of Table VIII show why this is so. The comparatively large amounts of induction by the white and the black screens narrow the limits so little because of the extreme rapidity with which sensitivity falls off in this zone. To narrow the limits even 3° , enough brightness must be induced, roughly speaking, to completely inhibit more than 200° of color.

TABLE VIII.

A. *Showing the rapid falling off in sensitivity of the extreme peripheral retina.*

Stimulus	Limen at 0°	Limen at 25°	Limen 5° from limit	Limen 3° from limit	Limen 2° from limit	Limen 1° from limit	Limit
Yellow	18°	35°	100°	150°	240°	330°	44°
Green	20°	40°	130°	145°	260°	345°	37°
Red	9°	17°	132°	150°	200°	320°	43°
Blue	9°	12°	130°	145°	200°	310°	53°

The following points, then, needed in our explanation of the influence of the white and black screens on the limits of color sensitivity have been established. (a) The white screen, which induces black, narrows the limits of sensitivity to red and yellow more than the black screen, which induces white, because neither screen narrows the limit more than 5°, and within this zone of 5°, red and yellow are inhibited by black more than by white. (b) The limits of blue and green are narrowed by the black screen more than by the white screen, because within this zone of 5°, as at the center, these colors are inhibited more by white than by black. But they are narrowed less by the black screen than might be expected from the inhibitive action of white found to obtain at the center, because as we go towards the periphery, the difference between the inhibitive actions of white and black decreases. And (c) neither screen narrows the limits for any color more than 5°, because within the zone 5° from the limits, the sensitivity falls off so abruptly from point to point that more brightness action is required to change the limits beyond this amount than either the white or the black screen induces.

We have explained the limits of sensitivity to the four colors when black and white screens are used. We have still to explain the results obtained with the gray screen. Since it causes no brightness induction, we might expect our widest limits to occur with this screen. Table V and VI, however, show that while this is true to some extent for blue and green, it is not true for red and yellow. The limits for red and yellow with the gray screen

of the brightness of the color are in each case slightly narrower than with the black screen and wider than with the white. As we are still working on this point, we do not at present feel justified in saying anything final by way of explanation. We may point out, though, that red and yellow darken in passing into the peripheral field of vision. The black screen tends to lessen this effect by contrast, and the white screen to augment it. It seems reasonable to expect, then, that the black screen, which lessens, by means of the white contrast, the amount of black fused with these colors in darkening, would widen their limits; and that the white screen, which increases it by means of black contrast, would narrow their limits, as compared with the gray screen, which exerts no effect at all. We can speak only tentatively, however, until the amounts of brightness dealt with in each case can be more accurately ascertained.

C. The Effect of the Induction of the Surrounding Field upon the Color Limens.

In order to estimate the effect of the induction of the surrounding field upon the limen of sensitivity to the different colors, the limens of color were determined at the center, and at 15° , 25° , and 30° of excentricity in the peripheral retina (*a*) when the surrounding field was of the gray of the brightness of the color; (*b*) when it was white; and (*c*) when it was black.

The preëxposure was in each case to the gray of the brightness of color. The limen was determined as follows: The stimulus composed of sectors of the color and the gray of the brightness of the color at the excentricity for which the limen was to be determined, was placed on the motor behind the campimeter screen. The proportions of the sectors were changed until the observer made the judgment of just noticeable color. Judgments were taken in ascending and descending series, and the average was taken as the value of the limen.

The results show that the influence of the brightness of the surrounding field upon the color limen is as follows:

1. The limen is lowest when the surrounding field is of the gray of the brightness of the color.

2. The difference in the effect of the white and black screens upon the limen increases from the fovea outwards.

3. For yellow and green the limen is highest when the field is black and the induction white, and lower when the field is white and the induction black.

4. For red and blue, the limen is highest when the field is white and the induction black, and lower when the field is black and the induction white.

5. The difference in the effect of white and black screens on the limens is not so great as one at first thought might be led to expect from the results obtained by the objective mixing of white and black with color in the central retina.

The results for Observer *A* are given in detail in Table IX.

D. Explanation of the Effect of the Induction of the Surrounding Field upon the Color Limens.

We have, then, the following facts to explain: (1) The limen of sensitivity to color is lowest when the surrounding field is of the gray of the brightness of the color. This is what should be expected, because in case of this screen there is no induction present to fuse with the color sensation, and to affect the limen of sensitivity. (2) The difference in the effect of the white and black screens increases from the fovea outwards. This is because the sensitivity of the retina to brightness contrast increases from the fovea outwards, as the table for the amounts of induction shows. More white and black, then, are induced, and as our results with objective mixing show, the greater are the amounts of white and black mixed with color, the greater is the difference between the inhibitive actions of equal amounts of each.²⁶ (3) The limen of sensitivity to yellow and green is high-

²⁶ A rough demonstration of this can be easily made as follows. Set up two discs, of blue for example, side by side on color-mixers. Add a small sector of white to the one and an equal sector of black to the other, and observe the apparent saturations of each. Repeat the observation several times, each time increasing the sectors of black and white by equal amounts. It will be observed that the difference in the apparent saturations of the equally saturated discs becomes greater and greater, until at 180° the disc to which white was added appears almost colorless while the disc to which black was added is still a well-saturated dark blue.

est when the surrounding field is black, and lower when the surrounding field is white. This is in accord with the general law of the inhibitive action of white and black on color. That is, since color is inhibited less by black than by white, we should expect in terms of the law that the limen of color would be lower with the white screen which induces black than with the black screen which induces white. The limens obtained for yellow and green present no exception to this law. (4) The limens for red and blue are highest when the surrounding field is white, and lower when the surrounding field is black. But this is in apparent contradiction to our general law of the relative inhibitive action of white and black upon the colors. An explanation of why we have this apparent contradiction in case of red and blue and not in case of yellow and green may be readily found, however, in the relative amounts of contrast induced by the white and black screens across these colors. Table XII (p. 142) shows the amount of contrast that is induced by the white and the black screens across the grays of the brightness of the colors. As we have already mentioned, the white screen induces more black across the grays of the brightness of red and blue, than of yellow and green; the black screen induces more white across the grays of the brightness of yellow and green, than of red and blue. For example, Observer *A* estimated the amount of black induced by the white screen at 25° in the horizontal temporal meridian as 135° for yellow, and 155° for green; and the amount of white induced by the black screen as 110° for yellow, and 60° for green. There is, then, less white induced across these two colors by the black screen than there is black induced by the white screen. In spite of this, however, the greater inhibitive power of this smaller amount of white is sufficient to raise the limen of sensitivity to yellow and green slightly higher than it is raised by the less inhibitive power of the larger amount of black. For red and blue, on the other hand, the black induced by the white screen is estimated as 230° for red, and 290° for blue; while the white induced by the black screen is estimated as only 28° for red and only 12° for blue. In these cases there is a very much greater amount of black induced than of white.

And this very much greater amount of black is sufficient to raise the limen of sensitivity to the colors with which it is fused higher than it is raised by the very small amount of white, in spite of the fact that when equal amounts of black and white are mixed with a color, its saturation is inhibited much more by white than by black. (5) The difference in the effect of white and black screens on the limens is not so great as one at first thought might be led to expect from the results obtained by the objective mixing of white and black with color in the central retina. This may be explained as follows. (1) The relative amounts of white and black induced upon the different colors by the screens vary greatly. We have thus not a simple case of a difference in the inhibitive action of equal amounts of black and white. In case of yellow and green, for example, there is so much more black induced than white that the white raises the limen very little more than the black. And in case of red and blue, the amount of black induced is so very much in excess of the white that the limen is raised even more by the black than by the white. It is not raised much more, however, (even less than the excess for white in case of yellow and green), because (*a*) the excess of black induction is not sufficiently large greatly to overweigh the superior inhibitive power of white; and (*b*) the difference between the inhibitive powers of white and black is high for red and blue, especially for blue. (2) The difference in the inhibitive power of white and black on colors decreases from the center to the periphery of the retina. Thus not so great a difference is found in the limens for white and black screens in the peripheral retina as one might be led to expect from the amounts of induction present. An inspection of the table shows that the difference in the limens for the white and black screens increases from the center towards the periphery, but this increase caused by the greatly increased amounts of induction²⁷ is not so great as it would have been, were there no decrease in the difference in the inhibitive power of white and black on the different colors.

²⁷ It has already been shown, footnote, p. 121, that the greater are the equal amounts of white and black added to color, the greater will be the difference in the inhibitive actions exerted by these equal amounts.

TABLE IX

A. Showing the limens of color sensitivity with screens of white, black, and gray of the brightness of color.

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen with screen of gray of brightness of color	Limen with white screen	Limen with black screen
Yellow	0°	18°	22°	28°
	15°	22°	25°	35°
	25°	35°	50°	65°
	30°	50°	80°	95°
Green	0°	20°	22°	28°
	15°	27°	30°	35°
	25°	40°	50°	75°
Red	0°	9°	13°	10°
	15°	9°	19°	15°
	25°	17°	30°	23°
	30°	25°	50°	29°
Blue	0°	9°	17°	10°
	15°	10°	25°	12°
	25°	12°	35°	18°
	30°	20°	40°	30°

We have explained the effect of the induction of the surrounding field on the limits of color sensitivity, and on the limens of sensitivity. As we have said, the effect on the limit takes place in the extreme peripheral retina; the effect on the limen has been measured in the more central regions of the retina,—at 0°, 15°, 25°, and 30° of excentricity. We have remaining to compare the effect of the induction of the surrounding field in the extreme peripheral retina, as estimated by the limit, with its effect in the more central regions, as estimated by the limen, and in turn to determine how both sets of effects harmonize with our law of the inhibitive action of brightness on the colors. The comparison of the results obtained by the two methods for each of the colors is as follows:

1. For yellow, the limen of sensitivity was lower with the white screen but its limit was wider with the black screen. The effect of the screen upon the limen for this color is in accord with our general law of the relative inhibitive action of white and black upon the colors; and the effect of the screen on the limit

is in accord with its exception formulated for the extreme peripheral retina; that is, that in the region 5° from the limit for yellow, black inhibits yellow more than white does.

2. For green, the limen was lower and the limit was wider with the white than with the black screen. The effect of the induction of the screens, then, on both limens and limits, is in accord with our general law.

3. For red, the limen was lower and the limit was wider with the black than with the white screen. The effect of the induction of the screens on the limen is not in accord with our general law that white inhibits color more than black; however, the exception is readily explained by the much greater amount of black than of white that is fused with the color sensation by the induction of the screens. The effect on the limit is in accord with our exception to this law formulated for the extreme peripheral retina; that is, that within the region 5° from the limit of sensitivity to red, black inhibits red more than white does.

4. For blue, the limen was lower with the black screen, but the limit was wider with the white screen. The effect of the induction of the screen on the limen is not in accord with our general law, but the exception may be explained, as in case of red, in terms of the very much greater amount of black induced by the white screen than of white induced by the black screen. We have here, however, an apparent paradox with regard to the limits. That is, since the law of the relative inhibitive action of white and black is the same at the limit for blue as it is at the center, we might expect that if the black induction was sufficiently in excess of the white to make the limens higher for the white screen than they were for the black, it would also correspondingly make the limits narrower for the white screen than for the black. The reverse, however, it will be remembered, was true. The reason for this lies in the fact often mentioned previously that blue lightens in the periphery, so that near its limit of sensitivity it is not in so much greater contrast to the white screen than to the black screen as it is in the center. For example, for Observer *A* the brightness of blue in the periphery

equalled gray No. 28. In the periphery, then, the amount of white induced by the black screen is sufficient to inhibit the blue sensation more than it is inhibited by the amount of black induced by the white screen. It may be mentioned, however, that the difference between the limits for blue with the white screen and with the black screen is smaller for all observers used than is the difference between the limits with these screens for any other color with which we worked (see Tables V and VI, p. 114).

3. *The Brightness of the Preëxposure.*

When making the color observation in the peripheral retina, the observer is given a short period of preparation before the stimulus is exposed, in which to obtain and hold a steady and accurate fixation. This introduces the factor of preëxposure, for during this period of preparation, the area which is to be stimulated by color receives a previous stimulation. It seems strange to the writer that this factor, which exerts a greater influence over the extent of color sensitivity than any we are examining, with the possible exception of large changes in the general illumination, should have been so generally overlooked in the work of earlier investigators. It has always been considered a sufficient precaution to eliminate all color from the preëxposure. This, however, is not enough. It should also be of the same brightness as the color by which the eye is to be stimulated. If not, it gives an after-image which mixes with the succeeding color sensation and both reduces its saturation and modifies its color tone.²⁸ If the preëxposure is lighter than the stimulus color, it adds by after-image a certain amount of black to the succeeding color impression; if darker, it adds a certain amount of white. Since white inhibits color more than black, the effect of a dark preëxposure is to reduce the sensitivity to color more

²⁸ This action takes place apparently at some physiological level posterior to the seat of the positive, negative, and contrast color processes commonly supposed to be located in the retina. (See Ferree and Rand. *An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action.* Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297.)

than the effect of a light preëxposure.²⁹ But since both white and black as after-effect reduce the sensitivity to color, the eye is rendered more sensitive when no after-image is given, that is, when the preëxposure is of the same brightness as the color. The preëxposure should, therefore, be to a gray of the brightness of the color. No brightness after-image will be added to the succeeding color impression to modify either its saturation or its color tone. Even closing the eye, as is frequently done before stimulating, is equivalent to giving a black preëxposure.

No thought apparently was given by previous experimenters to the intense after-effect which follows the exposure of the eye to a brightness quality differing from that of the stimulus. Hess,³⁰ Fernald,³¹ and Thompson and Gordon,³² it is true, covered the stimulus before exposure with a card matching in quality the campimeter screen, but since the campimeter screen was not always of the same brightness as the color used for the stimulus, this by no means ruled out the effect of preëxposure. The motive of each of these experimenters seems to have been to standardize the observation for the effect of preëxposure, but no notion of its action sufficiently clear to guide them in formulating their technique seems to have been entertained. Since the action of the preëxposure is by way of arousing a brightness after-image, it is obvious that the preëxposure card should, as stated above, be matched in brightness to the stimulus color rather than to the screen.

In the articles, "*Colored After-Image and Contrast Sensa-*

²⁹ A very striking demonstration of the effect of preëxposure upon the sensitivity of the retina to color can be made for class or lecture room purposes as follows. Mount a sheet of the blue paper of the Hering series on cardboard. Cover one-half of another sheet of cardboard of the same size with white of the Hering series of papers, the other half with velvet black. Place this card immediately in front of the first card and fixate its center for 10 or 15 seconds. Remove and observe the comparative effect of the white and black preëxposures thus obtained upon the color impression gotten from the blue surface.

³⁰ Hess, C. loc. cit.

³¹ Fernald, G. M. Psychol. Rev., 1905, XII., p. 394; Psychol. Rev. Monog. Sup., 1909, X., No. 42, p. 17.

³² Thompson and Gordon. A Study of After-images on the Peripheral Retina. Psychol. Rev., 1907, XIV., p. 123.

tions from Stimuli in Which No Color Is Sensed,"³³ and "*The Fusion of Colored with Colorless Light Sensation.—The Physiological Level at Which the Action Takes Place*,"³⁴ the effect of the after-image due to previous brightness exposure upon color sensitivity has already been shown for both central and peripheral retina. The general fact need not further be dwelt on here. We do, however, need to show why in the peripheral retina the short pre-exposure which takes place while the eye is obtaining a steady fixation has so much effect upon the color stimulation immediately following. Two reasons are found for this. (a) The peripheral retina is extremely sensitive to short stimulation. While some slight variation is found at different angles of excentricity, the peripheral after-image reaches in general its maximal intensity with two or three seconds stimulation. This amount of time is usually consumed in obtaining fixation, hence in each observation there is fused with the color sensation about as strong a brightness after-image as can be aroused. For this reason alone, it is readily seen why the brightness of the pre-exposure is of so much greater consequence in the peripheral retina than it is in the central retina, where the maximal strength of the after-image is obtained with from forty to sixty seconds stimulation. (b) There is apparently no latent period in case of the peripheral after-image. It flashes out at full intensity immediately upon the cessation of the stimulus. Thus, there is no possibility of escaping the full effect of the brightness after-image upon the stimulus color, as might happen in the central retina, where the latent period obtains, if there were a very short exposure to the stimulus color.

If when working with the campimeter, for example, a black card is used to cover the stimulus-opening during the period of preparation, an intensive white after-image is aroused which

³³ Ferree and Rand. Psychol. Rev., 1912, XIX., pp. 195-239.

³⁴ For abstract of the article, see Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297. The article will soon be published in full. See also Ferree, C. E. Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort. Transactions of the Illuminating Engineering Society, 1913, VIII., pp. 40-60.

fuses with the succeeding color sensation, strongly reducing its saturation. If, on the other hand, a white card is used, a black after-image is obtained, which, according to our law of the action of the achromatic sensation upon color, has less effect than the white after-image upon blue and green, and also upon red and yellow if the after-image is sufficiently strong to narrow the limits to red and yellow more than 5° . In each case, the intensity of the after-image will in part depend on the brightness of the subsequent color exposure, the projection field. The after-image due to preexposure to white will be more intensive when blue than when yellow forms its projection field. The after-image from black will be more intensive when projected on yellow or green than on blue or red. If, however, a gray card of the brightness of the stimulus color be used as preexposure, there will be no after-image to modify the color sensation. The only brightness change acting upon it will be due to the slight adaptation to this gray during the short time of preexposure.

The method, then, of eliminating the effect of preexposure consists in making it of the brightness of the color to be used as stimulus. And in case the brightness of the color alters in passing from the center to the periphery of the retina, the brightness of the preexposure must be correspondingly altered. For example, at standard illumination, Hering Gray No. 41, or its equivalent should be used for preexposure to blue when the central retina is investigated. But for the peripheral retina, a much lighter gray should be used because in this region blue lightens by an amount depending upon the excentricity of the stimulation and in part upon individual variation.

A. Effect upon the Limens of Color and upon the Limits of Color Sensitivity.

To test the importance of preexposure, two methods of measurement were employed. In the first, the limen of color was obtained at 0° and at 35° on the temporal meridian, when the screen was of the gray of the brightness of color, and the preexposure was in turn to the same gray, to white, and to black. In the second method, the limits of color sensitivity were investigated under the same conditions of campimeter

screen and preexposure card. The results for Observer *A* are recorded in Table X and in rows 1, 4, 7, 10 of Table XI. They show in every case, (a) that the limen is raised and the limit is considerably narrowed when the preexposure is not to the gray of the brightness of the color, that is, when it gives a brightness after-image; and (b) that the limen is higher and the limit narrower when the preexposure is to black and its after-image is white, than when the preexposure is to white and its after-image black.³⁵ This is in accord with the law of the

³⁵ There is one exception to this statement. The limen for blue at 0° for both white and black preexposures is 13° . The following reasons may be given for this. (a) It is one of the fundamental laws of brightness after-images that the intensity of the after-image depends in part upon the brightness relation of stimulus to projection field. When the brightness difference between the stimulus and the projection field is small, a weak after-effect is obtained; when it is greater, a more intensive after-effect is obtained. Blue, as aroused in the central retina, is very near to black in brightness, and very far removed from white. We should then expect a very much more intensive after-effect of the exposure to white than to black when the projection field is blue. (b) The brightness relation of the surrounding field to the preexposure also exerts an effect on the intensity of the after-image given by the preexposure. When the surrounding field differs in brightness from the preexposure, contrast is induced. This contrast quality in turn also gives an after-image which mixes with and modifies the after-image given by the preexposure. When the surrounding field is of the gray of the brightness of blue, for example, and the preexposures are in turn white and black, the influence of the surrounding field is to make the after-image of white stronger than that of black. That is, when the preexposure is white, this white is strongly intensified by contrast with the surrounding field of dark gray, and in consequence the black after-image is strongly intensified. But when the preexposure is black, little intensification results by contrast with the surrounding field and little effect is had on the after-image. Both of these influences, then, tend to cause much more black to be added to a blue stimulus in the central retina as a result of preexposure to white than white to be added as a result of preexposure to black. The effect of this excess of black, as is shown by the table, is to raise the limen for blue for the white preexposure as much as it is raised by the black preexposure; in other words, to make the limens equal. At 35° in the periphery, however, the limen of blue is seen in the table to be higher when the preexposure is to black and the after-image white, than when the preexposure is to white and the after-image black. We have here a different case. The difference in the effect of white and black preexposures at 0° and at 35° is due to the fact that at 0° blue is very dark while at 35° in the periphery it has lightened until its brightness equals No. 35 gray. In the latter case (a) there is less difference than there was at 0° between the brightness relations of the stimulus to

action of brightness upon color and holds for all colors used. It might be expected from the exception to this law, mentioned on page 116, that the limits for red and yellow would be narrowed more by the black after-image than by the white. This is not found to be true because the effect of each after-image is sufficiently strong to narrow the limits of red and yellow more than 5° , and thus to carry the limits for these colors outside of the zone in which they are inhibited more by black than by white.

B. Combined Effect of Surrounding Field and Preëxposure upon the Limits of Color Sensitivity.

The effect of preëxposure upon color limits was also investigated when white and black screens were used. The results obtained are of interest in two regards. (a) They show under these typical conditions in what way and to what extent the inductive action of the screen combines with the effect of preëxposure to modify the limits of color. (b) They help to explain some of the conflicting results obtained by previous investigators who did not carefully standardize their observations with reference to the effect of preëxposure and surrounding field. A few points may be noted in advance of the tables showing the combined action of preëxposure and surrounding field upon the extent of color sensitivity. It is obvious that when the campimeter screen is either white or black and the preëxposure is to the same brightness quality, there will be no inductive

the white preëxposure and of the stimulus to the black preëxposure, and consequently less difference between the intensities of the after-images from these preëxposures; and (b) there is less difference than there was at 0° between the brightness relations of the surrounding field, which is of the brightness of blue at the point at which we are working, to the white preëxposure and of the surrounding field to the black preëxposure, and for this reason also, less difference between the intensities of the after-effect of the contrast induced by the surrounding field upon these preëxposures. For both reasons, therefore, the after-image from the white preëxposure at 35° , when projected on blue, is not so much more intense than the after-image from the black preëxposure, as it was at 0° . At 35° , then, in these experiments the white after-effect due to preëxposure to black is sufficiently intensive to raise the limen of blue higher by virtue of its greater inhibitive power than it is raised by the black after-image due to preëxposure to white.

action by the screen upon the preëxposure either to intensify or to weaken it. In this case both preëxposure and screen will add the same brightness quality to the stimulus color, the former by contrast, and the latter by after-image. The effect of this action upon the color limits is shown in Table XI, Column 4, rows 2, 5, 8, 11; and column 5, rows 3, 6, 9, 12. If, however, the preëxposure and the screen are different in quality, their action may be either antagonistic or supplementary, depending upon the brightness relations between the screen and the preëxposure, on the one hand, and between the screen and the color sensation fused with the after-image of preëxposure on the other. For example, if a black preëxposure and a white campimeter screen are used, the white screen will intensify the blackness of the preëxposure by contrast but will tend to darken the fusion of color sensation and white after-image, and thus will lessen the action of the latter upon the color. This effect is shown in Table XI, in column 4, rows 3, 6, 9, 12; and column 5, rows 2, 5, 8, 11. If, however, the preëxposure is black, and the campimeter screen is the gray of the stimulus color, the

TABLE X.

A. *Showing the effect upon the color limens of preëxposure of the gray of the brightness of the color used, of white, and of black.*

Stimulus	Surrounding field	Preëxposure	Limen at 0°	Limen at 35°
Yellow	gray no. 2	gray no. 2	18°	83°
		white	35°	105°
		black	45°	125°
Green	gray no. 8	gray no. 8	20°	100° ^{3a}
		white	33°	155°
		black	40°	180°
Red	gray no. 24	gray no. 24	9°	90°
		black	13°	135°
		white	20°	148°
Blue	gray no. 41 at 0° no. 35 " 35°	gray	9°	30°
		white	13°	40°
		black	13°	43°

^{3a} As green has a narrow zone of visibility, the limen was taken at 30°.

screen will intensify the blackness of the preëxposure by contrast, but will lighten the fusion of stimulus color and white after-image, thus will add to the action of the latter upon the color. This effect is shown in Table XI, columns 4 and 5, rows 1, 4, 7, 10.

TABLE XI.

A. Showing the combined effect of campimeter screen and preëxposure upon the limits of color sensitivity.

Stimulus	Campimeter screen	Limit with gray preëxposure of the brightness of the color	Limit with white preëxposure	Limit with black preëxposure
Yellow	gray no. 2	44°	40°	38°
	white	42°	42°	43°
	black	45°	43°	40°
Green	gray no. 8	37°	35°	31°
	white	36°	30°	25°
	black	34°	36°	25°
Red	gray no. 24	43°	38°	37°
	white	42°	38°	39°
	black	44°	43°	38°
Blue	gray no. 28	53°	42° ³⁷	42° ³⁷
	white	50°	42° ³⁷	48°
	black	49°	51°	42° ³⁷

Having seen from Tables X and XI the effect of preëxposure and the combined effect of preëxposure and surrounding field upon the limen and the limits of color, we may turn our attention to a third point of interest; namely, the explanation of some of the differences between our results and those obtained by earlier investigators in terms of the different conditions of preëxposure used. As Hess and Fernald alone have stated their conditions of preëxposure, we shall have to limit our discussion to them. Hess wished to find the comparative limits of color sensitivity. He attempted to standardize the intensity and the brightness of the stimuli used, and worked with white, black, and gray campimeter screens. The eye of the observer followed

³⁷ For the explanation of this decided narrowing of the limit for blue, see footnote, p. 108.

a moving fixation-point while the stimulus was exposed from time to time. In every case, the stimulus was covered by a card of the same brightness and quality as the screen. He turned the gray screen toward or away from the source of light until its brightness was such that the color disappeared in the periphery into a gray of the brightness of the screens. He thus worked with screens of the gray of the brightness of the color, of white, and of black, and with preexposures of the same brightness as the screens. In only one of these cases, namely, the first, has he eliminated the effect of preexposure. He found that for every color, the limit of sensitivity was widest with the gray screen, narrower with the black, and narrowest with the white. His results are in contradiction to ours with regard to the influence of these screens, when the factor of preexposure is eliminated (see p. 113). They are, however, very nearly confirmed by the results we obtained when the preexposure was of the same brightness as the screen (See Table XI). Had our illumination been slightly less, and consequently the induction from the white screen greater, our results would have been very similar to those of Hess.

Fernald, working with a white and a black background and using preexposures to match, obtained results that are similar to those of Hess for all colors except red, and even in this case the exception is only apparent. She says: "All the colors except the reds are perceived at a greater degree of eccentricity with the dark than with the light background. Red is seen as red to about the same degree of eccentricity with the dark as with the light background, but is seen as yellow or orange with the dark background at the same points at which it is seen as colorless with the light background."³⁸ The latter part of the quotation shows that the exception to Hess in case of red was due rather to a difference in the method of measurement than to a difference in result. She recorded as the limit of color the point at which the sensation took on any trace of a foreign quality. Although the red stimulus appeared as red-yellow in the periphery with the black screen, there was some red in the

³⁸ Fernald, G. *Psychol. Rev. Monog.*, 1909, X, p. 23.

sensation received from it at a greater angle of excentricity with the dark than with the light screen.

As was said above, the conclusion of Hess and of Fernald that the colors have wider limits with the black than with the white screen, is confirmed by our work at certain illuminations when white and black preexposures are used. But, since we do not obtain similar results when the influence of preexposure is eliminated and the effect of the brightness of the field determined in isolation from this factor, we maintain that their results were due to brightness conditions not connected with the surrounding field, but with the preexposure. Our contention is that many of the conflicting conclusions concerning the effect of background upon color limits have resulted from ignorance of the important factor of preexposure. Comparative color limits can be obtained with any screen only when the preexposure is to the gray of the brightness of the stimulus. This principle was used by Hess in his work with the gray screen, but apparently without a definite purpose and without knowledge of its importance.

4. *The General Illumination of the Retina.*

The effect of change of illumination was forced upon our attention early in the investigation of the factors that influence the color sensitivity of the retina. For example, in preliminary work done by the writer on a well-lighted porch on Long Island, changes in color tone were reported, when certain colors were compared in the central and in the peripheral retina, that are not found at all under the more intensive illumination of our optics-room, when neither of the curtains is drawn; and the peripheral limits of color were narrower by 5° to 12° . Furthermore, on a dark day, it was found that the limits of stimuli exposed through an opening in a white screen were reduced by about 4° as compared with the limits taken on a bright day. The change was less considerable with black and gray screens. The change in color tone was most conspicuous in case of green.³⁹ On dark days the green stimulus appeared as a pale unsaturated blue before becoming colorless in passing from the center to the periphery of the retina. This zone of blue was from 7° to 23°

³⁹ The green of the Hering series was used.

wide in different meridians of the retina with both white and black screens, but was wider with the black than with the white screen. On a sunny day, on the other hand, with the white screen green passed into bluish-green, then directly into gray, except in case of the upper regions where it appeared blue throughout a zone of about 4° in width. With the black screen, the blue zone was found only in the upper and temporal regions of the retina. The transition of green to yellow in the periphery that is generally reported in the literature was found in these experiments only when the gray screen was used. Yellow showed a color change that varied in amount with the degree of the general illumination. On a bright day, it appeared reddish-orange with the white screen. On a cloudy day, it was seen in the extreme periphery as a dark saturated red.

Working in our optics-room we found also that results taken on one day could not at all be duplicated on the following day. When the work was carried on under the most favorable conditions without special means of controlling illumination, namely, on bright days only, differences of 5° or more were found when the white screen was used. This necessitated a long series of observations if legitimate averages were to be obtained. Such a procedure is at best a poor makeshift and is besides of great disadvantage in many problems that come up in the work on color sensitivity. Particular instances of this may be found in investigations in which it is required to work in the region lying just within the limits of sensitivity, and in work on the after-images of stimuli in which no color is sensed. In the latter case the experiment requires that the stimulus be exposed just outside the limits of sensitivity determined with a given brightness condition, and that the observer should not be aware of the nature of the stimulus. In order to fulfill these requirements the experimenter must know the limits obtaining with a given brightness condition. It would be impossible to know this when the brightness conditions were subjected to the influence of changing illumination unless re-determinations were made at the beginning of each sitting and even frequently during its course. This would consume a great deal of time and would, besides,

only roughly fulfill the requirements of the problem. A further and still more important example of the disadvantage may be found in the task we had set ourselves, namely, to investigate from point to point the sensitivity of the retina to each of the principal colors for three backgrounds in at least sixteen different meridians. In this work it is obvious that unless a standard illumination were provided, all comparative work would have to be done at one sitting. This is impossible. When time is taken between observations to guard against fatigue, at least three hours is required merely to outline the limits of sensitivity for a given color with one background for only one-half of the retina. Even for this length of time there is no guarantee that the illumination has not altered. Thus at the outset of any extended investigation of color sensitivity, it is evident that without a standard illumination, results will be of little comparative value.

In order better to know our factor and the ways in which it operates, a systematic investigation of the influence of changes of general illumination was carried on in our optics-room, which is especially constructed to secure fine changes in illumination. Rough preliminary experiments showed that the primary effect of decreasing the illumination was an alteration of the amount of contrast induced across the stimulus by the campimeter screen. With the white screen, the increased induction was the most pronounced and was sufficient to cause large changes in the limits and in the color tone of the stimulus. In order to investigate this effect in detail, gradual changes of illumination covering a wide range were made by means of the curtains with which our optics-room is furnished, described on p. 86. Attention was given to the following points. (*a*) A quantitative estimate was made of the influence of change of illumination upon the brightness induction of the campimeter screen. (*b*) The effect of this induction upon the limits of color sensitivity was determined. (*c*) The limens of the colors were measured at different degrees of excentricity at different illuminations. And (*d*) the influence of change of illumination upon the effect of the preëxposure on the limens and limits of color was investigated. The degrees

of illumination chosen for comparison were the standard illumination, the method of obtaining which will be described later, and the decreased illumination mentioned above (see p. 95 and Tables I and II) for which the white-values of the stimuli were determined. Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles, the decreased 1.65 foot-candles.

A. Quantitative Estimate of the Influence of Change of Illumination upon the Induction of Brightness by the Surrounding Field.

The purpose of this investigation was to find out how much the induction from white and black screens⁴⁰ is affected by a change in the general illumination; and (b) how much induction is gotten at decreased illumination from the gray screen which matches the color in brightness at standard illumination. The induction in this latter case is caused by the change in the brightness relation between color and screens with decrease of illumination.⁴¹ The campimeter screens served as inducing surface, grays of the brightness of the four principal colors of the Hering series both at standard and decreased illumination were used in turn as stimuli, and the amount of induction was estimated upon a measuring-disc, made up of adjustable sectors of the gray of the stimulus and white or black, according to the screen used. The measuring-disc was mounted on a motor (see p. 87 and Fig. I) which could be moved along the graded arm of the campimeter to any position from 20° to 92°. The gray stimulus was exposed through the opening of the screen in the usual manner. Two preliminary precautions were observed. (a) Since

⁴⁰ White and black screens are chosen because they represent the extreme cases of the effect of change of illumination.

⁴¹ This latter determination is made to show that it is impossible to standardize the brightness of the surrounding field against the sudden and progressive changes of daylight that occur during the course of a single series of observations. These changes alter the brightness relation between the colored stimulus and the gray used as screen; therefore a match made at the beginning of a series will not hold throughout its course. For the same reason and to an equal degree the brightness relation between preexposure and colored stimulus changes with change of illumination. It is, therefore, equally impossible to standardize the brightness of the preexposure without some means of securing a standard illumination.

the brightness of the gray stimulus plus the induction of the screen was to be estimated by means of the measuring-disc, and since the brightness-value of the stimulus and of the disc changes with the amount of light that falls upon them, it was necessary to make sure before each measurement that the same amount of light fell upon each. This precaution was all the more necessary because the stimulus had to be placed behind the screen and the measuring-disc in front. In a given position of the apparatus, one or the other was apt to be shaded. The determination was made as follows: Measuring-disc, campimeter screen, and gray stimulus were all given the same brightness-value according to determinations made under conditions about which no doubt of the equality of the illumination of each could be entertained. Each was then placed in position for the experiment, and the position of the campimeter as a whole and of its various parts was adjusted until stimulus, screen, and measuring-disc were exactly matched in brightness-value. When an exact match was obtained we were guaranteed that all three were again equally illuminated. This precaution was particularly necessary in the investigation we are discussing in this section. It was carefully observed, however, throughout the entire work. (b) The question arose whether brightness induction comes to its maximal value at once in the peripheral retina. A determination of the intensity curve of the contrast sensation was accordingly made at various points in the peripheral retina. It showed that contrast increases strongly for the first few seconds of stimulation. For this reason it was found to be necessary to make the judgment concerning the amount of induction of the screen, just as long after the induction had commenced as was done in the experiments to determine color sensitivity. In the color experiments an interval has to be allowed before the stimulus is exposed during which the observer obtains a steady fixation. During this interval of preëxposure, the eye is being stimulated by the campimeter screen and by the card which covers the stimulus. To prevent the preëxposure card from giving a brightness after-image which would fuse with and modify the sensation immediately following, it should be chosen of a gray of the

brightness of the color. In the same way, an interval had to be given in which to secure steady fixation when the amount of brightness induction was being measured. In order, then, to have the judgments made in each case the same length of time after induction had begun it was necessary only to make the intervals of preëxposure of equal duration and to require that the judgments of each kind be made directly at the end of the preëxposure. In the case of the color experiments, the signal for the making of the judgment is the withdrawal of the preëxposure card and the exposure of the stimulus. For the judgments of induction, however, in which case the stimulus was the gray of the brightness of the color, it is obvious that no preëxposure card was needed, for preëxposure and stimulus were required by the conditions of the experiment to be the same. In this case, a word-signal had to be given to indicate the termination of the preëxposure interval and the instant at which the judgment was to be made.

Results when white and black screens were used.—Observing these precautions as to the equality of the illumination of stimulus, screen, and measuring-disc, and as to the length of time the induction had had in which to increase before the judgment was made, measurements were taken of the induction by white and black screens across grays of the brightness of the four principal colors at the illumination used. These measurements were made at various points of excentricity on the retina, and for both standard and decreased illuminations. The determination of the equality point between the stimulus and the measuring-disc was made as follows: The size of the white or black sector of the latter was changed until a preliminary judgment of equality was made. Then the j. n. d. on either side of this point was determined both by ascending and by descending series and an average of the results was taken as the value of the induction. Measurements were taken at 25° and at 40° on the temporal meridian, and at 55° and 70° on the nasal. The conditions at the nasal 55° were very similar to those at 25° on the temporal side. The measurements at 70° nasal were midway in value between those at 25° and at 40° on the temporal. The 40° point is very near the limits of color sensitivity in this meridian, and the induction here is very great. For one ob-

server, the darker stimuli appeared black at this point, when the white background was used. In such cases, the difference between the induction at standard and at decreased illumination is more clearly shown by the observations made at 25° temporal meridian and at 55° and 70° nasal meridian than at 40° temporal. We have, however, chosen for two reasons to present in the following table only the results obtained in the temporal meridian. (a) The results obtained in this meridian demonstrate sufficiently well all the facts that need be taken into consideration. Space will not, therefore, be given to the results for both meridians. (b) The second point of our problem requires us to correlate the increased amount of induction caused by a given decrease of illumination with the change in the color limits it produces. The limits of color sensitivity can be more easily investigated in the temporal meridian because the sensitivity to some colors extends in the nasal region beyond the 92° point, which is the limit of measurement for the apparatus we used. This is true in particular in case of Observer C as may be seen in Table VI. Both purposes of the investigation are, then, better satisfied by results obtained in the temporal meridian.

The results show in general the following facts.

(1) The amount of induction increases with the distance from the fovea.

(2) The amount of induction increases with decrease of illumination.⁴²

(3) The amount of induction from the white screen is greater than that from the black screen.^{42a}

(4) The amount of increase of induction at decreased illumination is greater in case of the white screen than in case of the black screen.

(5) The white and black screens induce most across the stimuli that are farthest removed from them in brightness, and least across those which are nearest to them in brightness. That

⁴² This statement is meant to apply only to the range of illumination worked with. The induction was not measured when the illumination was very low, nor when it was very intensive.

^{42a} An exception to this statement of result occurs in case of gray No. 2 at 40° . This stimulus is so near to white in brightness that the induction across it, according to the principle stated in (5) above, is greater for the black screen than for the white.

is, the white screen induces more black across the gray of the brightness of blue than across the gray of the brightness of yellow; the black screen induces more white across the gray of the brightness of yellow than across the gray of the brightness of blue.

Results are given in detail in Tables XII and XIII. Table XII gives the results for observer *A* taken on the temporal meridian, and Table XIII, the results for Observer *C* for the same meridian. There is some difference in the amount of induction reported by the different observers, but since the preceding general statement of results is clearly borne out in every case, it is not deemed necessary to give space to results from all the observers used. In these tables, column 1 gives the degree of excentricity at which the observation was made; columns 2, 3, and 4, show respectively the stimulus used, and the amounts of induction from the white and from the black screens at standard illumination. Columns 5, 6, and 7, give the same data for decreased illumination.

TABLE XII.

*A. Showing the amount of contrast induced by the white and the black screens at standard and decreased illumination upon the grays of the brightness of the colored stimuli at standard and at decreased illumination.*⁴³

Fixation	Standard illumination			Decreased illumination		
	Stimulus (gray of brightness of each of the four colors at standard illumination)	Amt. induction of white screen	Amt. induction of black screen	Stimulus (gray of brightness of each of the four colors at decreased illumination)	Amt. induction of white screen	Amt. induction of black screen
25°	gray no. 2	Black 135°	White 110°	gray no. 2	Black 220°	White 170°
	gray no. 8	" 155°	" 60°	gray no. 6	" 270°	" 80°
	gray no. 24	" 230°	" 28°	gray no. 41	" 320°	" 40°
	gray no. 37	" 290°	" 12°	gray no. 20	" 330°	" 30°
40°	gray no. 2	" 200°	" 300°	gray no. 3	" 320°	" 360°
	gray no. 8	" 300°	" 132°	gray no. 5	" 360°	" 180°
	gray no. 24	" 360°	" 60°	gray no. 50	" 360° ⁴⁴	" 0°
	gray no. 29	" 360°	" 28°	gray no. 13	" 360°	" 100°

⁴³ It is obvious that the method used in this and the following tables of expressing the amount of brightness induction gives an underestimation.

TABLE XIII.

Observer C.

25°	gray no. 2	Black 70°	White 55°	gray no. 2	Black 130°	White 70°
	gray no. 8	" 84°	" 48°	gray no. 6	" 155°	" 59°
	gray no. 24	" 93°	" 30°	gray no. 40	" 187°	" 45°
	gray no. 37	" 160°	" 15°	gray no. 17	" 244°	" 22°
40°	gray no. 2	" 110°	" 200°	gray no. 3	" 216°	" 340°
	gray no. 7	" 142°	" 160°	gray no. 4	" 230°	" 320°
	gray no. 24	" 180°	" 95°	gray no. 50	" 360° ⁴⁴	" 0°
	gray no. 29	" 214°	" 35°	gray no. 7	" 300°	" 108°

Results when the gray screen matching the colored stimulus in brightness at standard illumination is used. It was necessary to perform the experiments bearing on this point at decreased illumination only. For them the campimeter screens which matched in brightness the four principal colors of the Hering series at standard illumination served as inducing surfaces. For

Suppose, as is shown in Table XII, that No. 24 Hering gray has been darkened by induction until it matches in brightness a disc made up of 230° of black and 130° of the No. 24 gray. The amount of induction is greater than is represented by the 230° of black because the induction has not lessened the amount of light coming to the eye from the gray paper while the addition of 230° of black to the measuring-disc has cut off approximately $\frac{2}{3}$ of the light coming from the gray paper. That is, in the one case enough black has been added by induction to reduce 360° of No. 24 gray to the given point in the brightness scale, while in the other enough black was added by direct mixing to lower only 130° of No. 24 gray to this point in the scale. Moreover, the underestimation will be increased by this method of measuring in proportion as the amount of induction is increased because the greater the induction is the more black and the less gray will have to be used in the measuring-disc. All that can be said accurately is that a certain gray darkened or lightened by induction matches in brightness a gray made up of a certain amount of the given gray plus a certain amount of black or white. The exact amount of the induction can not be separated out. Further just because the brightness added by contrast does not alter the amount of light coming to the eye while the brightness added in any method of measurement does change this amount of light, the writer knows of no way by which an exact expression can be obtained. The method she has used, however, does serve as a means of comparing the amounts of induction occurring under different conditions sufficiently accurately for her purpose at this point.

"The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match thus could not be attained with black 360° as the table indicates.

the contrast surfaces, grays of the brightness of these colors at decreased illumination were chosen. The methods of measuring, precautions in working, parts of the retina investigated, etc., were the same as in the preceding determinations. The following general statement of results may be made.

1. At the 25° point the brightness of yellow was found not to have changed at all with the decrease of illumination produced by changing the illumination from the value selected as standard to the value selected for the comparison; the brightness of green lightened by an amount equal to the difference between No. 8 and No. 6 of the Hering series of grays; red darkened by an amount equal to the difference between No. 24 and No. 40; and blue lightened by an amount equal to the difference between No. 32 and No. 20. The amount of induction by the gray screen of the original brightness of the color upon the gray stimulus of the brightness of the color as altered by the decreased illumination, expressed in terms of Hering white and black, was for yellow 0° , for green 60° of white, for red 27° of black, and for blue 20° of white.

2. At the 40° point, the yellow darkened by an amount equal to the difference between No. 2 and No. 3 of the Hering grays; green lightened by an amount equal to the difference between No. 8 and No. 5; red darkened by an amount equal to the difference between No. 28 and No. 50; and blue lightened by an amount equal to the difference between No. 28 and No. 13. The amount of induction produced by these changes was for yellow 280° of black, for green 130° of white, for red 360° of black, and for blue 60° of white. These results are shown in detail in Table XIV.

(B.) *The Effect of These Amounts of Induction upon the Limits of Color Sensitivity.*

In order to obtain an estimate of the range of effect upon the limits of color sensitivity of the induction of the screens at standard and at decreased illumination, the breadth of the color zones was determined at both illuminations (*a*) when white and black served in turn as campimeter screens; and (*b*) when a gray matching the color in brightness at standard illumination was

TABLE XIV.

A. Showing the amount of contrast induced at decreased illumination on grays of the brightness of the colors at decreased illumination by the gray screens matching the colors in brightness at standard illumination.

Fixation	Stimulus	Screen	Amount of Induction
25°	gray no. 2	gray no. 2	0
	gray no. 6	gray no. 8	white 60°
	gray no. 41	gray no. 24	black 27°
	gray no. 20	gray no. 37	white 20°
40°	gray no. 3	gray no. 2	black 280°
	gray no. 5	gray no. 8	white 130°
	gray no. 50	gray no. 24	black 360° ⁴⁵
	gray no. 13	gray no. 29	white 60°

used. The preëxposure was in each case to gray of the same brightness as the stimulus at the illumination used.

Results when white and black screens were used. When the stimulus color is gotten by reflection from a pigment surface, two factors operate to give a change of result when the illumination is decreased. (1) There is a decrease in the amount of colored light coming to the eye. (2) There is an increase in the inductive action of the screen due to the change in the brightness relation of the stimulus to screen and to the increased sensitivity of the eye to brightness contrast at decreased illumination.

In order to find out how much of our results with the white and black screens should be attributed to the decrease in the amount of colored light coming to the eye produced by the decreased illumination, and how much to the increased inductive actions of the screens, the limits of sensitivity were also determined at both illuminations with the screens of the gray into which the color disappears in the peripheral retina. From the values obtained with the three screens at both illuminations, the amount of change due to decrease in the amount of colored light coming to the eye and the amount due to induction by the white and black screens were calculated as follows. (a) From

⁴⁵ The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match could not be thus attained with black 360° as the table indicates.

the number of degrees expressing the limits for a given color at standard illumination with a screen of the brightness of the color at that illumination was subtracted the number expressing its limit at decreased illumination, with a screen of the brightness of the color at the decreased illumination. That this gave the number of degrees the zone of sensitivity was narrowed by the decrease in the energy of the stimuli, may be said with the following qualification. If there is any influence upon color sensitivity of the local brightness-adaptation of the retina produced by the change in the general illumination, it is, of course, included in this effect. But, since this influence would have to be brought about by previous exposure to the illumination in question, it can be reduced to a minimum by guarding against an exposure to it for any considerable length of time. The effect of whatever adaptation there may be, however, can not be isolated or separated out from the above result, and the value expressing the amount the limit is narrowed by the actual decrease of the energy of colored light coming to the eye cannot, strictly speaking, be obtained. But it is probable that the adaptation effect is not sufficiently strong to influence the limits, since the sensitivity of the extreme peripheral retina falls off very abruptly from point to point. The difference, then, between the color limit obtained at standard illumination and the limit at decreased illumination, when in both cases there is no brightness induction from the screen, may be said to approximate the effect upon the limits produced by the decrease in the amount of colored light coming to the eye. (b) Figures can be obtained, however, from our results, which express the amount by which the zones are narrowed by the change in the inductive action of the white and black screens produced by decreasing the illumination, that are not open to theoretical questioning; for the influence of local brightness-adaptation, if there be any, is a constant for all screens at the same illumination. If then, the number of degrees which expresses the limits of sensitivity for either the white or the black screen at decreased illumination is subtracted from the number expressing the limit with a screen of the gray of the brightness of the color at this illumination, the result will rep-

resent the extent to which the limit was narrowed by the action of induction alone.

The results show in general the following facts:

1. At standard illumination, induction from the white screen narrows the limits of yellow and red; induction from the black screen narrows the limits of blue and green. The difference is in no case more than 4° .

2. At decreased illumination, the induction from the white screen narrows the limits of all the colors much more considerably than does the induction from the black screen.⁴⁶

3. The values expressing the narrowing of the limits caused by decrease of illumination without induction, are greatest in case of those colors which undergo maximum change of brightness in passing into the periphery, namely, for blue and red.

We have shown by the results of the preceding section, that the increased induction produced by decrease of the general illumination is greater for the white screen than for the black, and, by the results of this section, that this increase is effective to the extent of narrowing the limits of sensitivity to all colors from 5° to 13° with this screen. With the black screen, the limits were narrowed from 0° to 6° . At standard illumination, the limits were narrowed only from 1° to 4° with either the white or the black screen.

Results in detail are given in Tables XV and XVI taken from the temporal meridians of the observers whose observations are recorded in Tables XII and XIII. In column 1, Tables XV and XVI, is given the stimulus. Column 2 shows the limit of sensitivity to the stimulus at standard illumination with a screen of a gray of the brightness of the color at standard illumination; column 3 shows the limit with a white screen; and column 4 with a black screen. Column 5 shows the limit at decreased illumination with a screen of the brightness of the

⁴⁶For Observer *A* the results for green present an exception. At the decreased illumination used the green stimulus appeared bluish in the central retina. The induction of the black screen caused it to appear as a pale blue at a comparatively slight degree of excentricity. According to our definition of color limit, this point is the limit of green. It is, however, obvious that the exception is due rather to the qualitative than to the quantitative effect of brightness upon color.

color at decreased illumination; column 6 shows the limit with a white screen; and column 7 with a black screen.

TABLE XV.

A. Showing the color limits at standard and decreased illumination (a) with gray screens of the brightnesses of the colors at the illumination used; and (b) with white and black screens.

Stimulus	Standard Illumination		Decreased Illumination			
	Limit with gray screen of brightness of color at standard illumination	Limit with white screen	Limit with black screen	Limit with gray screen of brightness of color at decreased illumination	Limit with white screen	Limit with black screen
Yellow	44°	42°	45°	43°	35°	43°
Green	37°	36°	34°	36°	31°	27°
Red	43°	42°	44°	40°	31°	40°
Blue	53°	50°	49°	49°	36°	43°

TABLE XVI.

Observer C.

Yellow	49°	46°	50°	46°	36°	44°
Green	44°	42°	40°	41°	28°	33°
Red	45°	41°	45°	41°	34°	41°
Blue	56°	55°	53°	50°	38°	44°

Tables XVII and XVIII to show the following facts:

(a) How much the decrease of illumination narrowed the limits of color sensitivity by causing a decrease in the energy of the light-waves coming to the eye. This was determined by subtracting the value of the limit at decreased illumination with the screen of a gray of the brightness of the color at decreased illumination from its value at full illumination with the gray screen of the brightness of the color at full illumination. (b) How much the limits were narrowed by the action of the white and black screens at decreased illumination. This was ascertained by subtracting the values of the limit with the white and the black screen at decreased illumination from the value of the limit at decreased illumination with the gray screen of the brightness of the color at this illumination. (c) How much

more the limits were narrowed by the white and the black screens at decreased than at full illumination. This was computed for the white screen, for example, as follows: The quantity, limit at decreased illumination for gray screen of brightness of color at decreased illumination, minus limit for white screen at decreased illumination, is subtracted from the quantity, limit at full illumination for gray screen of brightness of color at full illumination minus limit for white screen at full illumination. A similar computation was made for the black screen.

TABLE XVII.

A. *Showing (a) how much the limits were narrowed by decrease in the amount of colored light coming to the eye; (b) how much they were narrowed by increased induction of white and black screens at decreased illumination; and (c) how much more they were narrowed by induction of white and black screens at decreased than at full illumination.*

Stimulus	How much limits were narrowed by decrease in amount of colored light coming to the eye	How much limits were narrowed by induction of white screen	How much limits were narrowed by induction of black screen	How much more limits were narrowed by white screen at decreased than at full illumination	How much more limits were narrowed by black screen at decreased than at full illumination
Yellow	1°	8°	0°	6°	1°
Green	1°	5°	9°	4°	6°
Red	3°	9°	0°	8°	1°
Blue	4°	13°	6°	10°	2°

TABLE XVIII.

Observer C.

Yellow	3°	10°	2°	7°	3°
Green	3°	13°	8°	11°	4°
Red	4°	7°	0°	3°	0°
Blue	6°	12°	6°	11°	3°

Results when a gray screen matching the color in brightness at standard illumination is used. In these experiments a determination was made of the amount the limits of sensitivity are changed by the brightness induction caused by the alteration of

the brightness relation between stimulus and screen with decrease of illumination, when a screen is used which matches the color in brightness at standard illumination. This determination was made as follows.

An estimate was made of the amount the limits were narrowed by decrease of illumination when a screen of the brightness of the color at standard illumination is used for both standard and decreased illuminations. From this result was subtracted the amount the limits were narrowed by decrease of illumination when the screen is made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. It is given in Table XIX.

TABLE XIX.

A. Showing how much the color limits were narrowed at decreased illumination by the induction of the screen which matched the color in brightness at standard illumination.

Stimulus	Screen of brightness of color at decreased illumination	Limit	Screen of brightness of color at standard illumination	Limit	Amount limit was narrowed by change in brightness relation between stimulus and screen caused by decreased illumination
Yellow	gray no. 3	43°	gray no. 2	41°	2°
Green	gray no. 5	36°	gray no. 8	29°	7°
Red	gray no. 50	40°	gray no. 24	33°	7°
Blue	gray no. 13	49°	gray no. 28	46°	3°

(C.) The Effect of These Amounts of Induction upon the Limens of Color at Different Degrees of Excentricity.

We have shown the effect of decreasing the general illumination upon the color sensitivity of the peripheral retina with gray, white, and black screens by the effect on the limits of sensitivity. This is only an indirect means of estimating its influence, for the results obtained cannot be translated into terms of direct measurement, owing to the irregular decrease in sensitivity of

the peripheral retina from the fovea outwards. In this section, we shall measure the influence of changes of illumination directly by the changes produced in the limen of sensation at various angles of excentricity. As in the previous section, measurement will be made of the effect upon sensitivity (*a*) of the decrease in the amount of colored light coming to the eye, produced by the decrease of illumination, (*b*) of the difference in the inducing power of the white and black screens, and (*c*) of the change in the brightness relation of stimulus to background.

To determine the first of these three points, a campimeter screen had to be selected that gave no brightness contrast with the stimulus. To provide for differences in the brightness of the colors at the different points observed for the two illuminations at which we worked, a preliminary determination of the brightness of the sensation at these points was made at both illuminations by the flicker method. The brightness of the screen was chosen in each case of the brightness of the color according to these determinations. To eliminate the effect of preëxposure, the stimulus previous to exposure was in every case covered by a gray of the brightness of the color for the illumination used at the point of the retina at which we were working. Thus no brightness after-image was carried over to exert an inhibitive action upon the color sensation. The stimulus was a disc compounded of the sectors of the color, and of the gray of the brightness of the color for the illumination used at the point of the retina under investigation. The proportions of the sectors were altered until the observer gave the judgment of just noticeable color. The average of judgments made in ascending and descending series was chosen as the final value of the limen. The difference between the limens at standard and decreased illumination was taken as the measure of the loss in intensity which the stimulus had sustained by the decrease of illumination.

The effect upon the color limen of the increased induction from the white and black screens was shown by the same method, with the exception that the white and black screens were substituted for the gray of the brightness of the color. The stimulus was a disc composed of sectors of color and gray of the brightness of

the color at the angle of excentricity at which the determination was made.

The effect of the change in the brightness relation between the stimulus color and the screen produced by decrease of illumination was shown as follows. An estimate was made of the amount the limens are raised by the decrease of illumination when a screen was used for both standard and decreased illumination that had a brightness-value equal to the color at standard illumination. From these results was subtracted the amount the

TABLE XX.

A. Showing how much the limens of sensitivity were raised at the fovea, and at points 15°, 25°, 30° from the fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye produced by the decrease in the general illumination.

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen at standard illumination with screen of brightness of color at standard illumination	Limen at decreased illumination with screen of brightness of color at decreased illumination	How much limen was raised at decreased illumination
Yellow	0°	18°	20°	2°
	15°	22°	32°	10°
	25°	35°	40°	5°
	30°	50°	65°	15°
Green	0°	20°	20°	0°
	15°	27°	28°	1°
	25°	40°	50°	10°
Red	0°	9°	11°	2°
	15°	9°	13°	4°
	25°	17°	25°	8°
	30°	25°	45°	20°
Blue	0°	9°	10°	1°
	15°	10°	13°	3°
	25°	12°	15°	3°
	30°	20°	40°	20°

limens were raised by decreasing the illumination when the screens were made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. These results are of particular importance because they show that the influence of the brightness of the surrounding field can not be eliminated even when a screen of the brightness of the color is used unless some means be had of maintaining the general illumination of the room constant.

Table XX shows how much the limens of sensitivity were raised at the fovea and at points 15° , 25° , and 30° from the

TABLE XXI.

A. Showing the color limens at standard and decreased illuminations with white and with black screens.

Stimulus	Point on horizontal temporal meridian at which limen was taken	White screen		Black screen	
		Limen at standard illumination	Limen at decreased illumination	Limen at standard illumination	Limen at decreased illumination
Yellow	0°	22°	25°	28°	30°
	15°	25°	50°	35°	45°
	25°	50°	80°	65°	85°
	30°	80°	125°	95°	113°
Green	0°	22°	25°	28°	30°
	15°	30°	36°	35°	43°
	25°	50°	75°	75°	220°
Red	0°	13°	20°	10°	14°
	15°	19°	35°	15°	21°
	25°	30°	55°	23°	35°
	30°	50°	330°	29°	58°
Blue	0°	17°	22°	10°	12°
	15°	25°	40°	12°	17°
	25°	35°	60°	18°	25°
	30°	40°	90°	30°	60°

fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye pro-

duced by the decrease in the general illumination. The results of this table may be generalized as follows:

1. The limen of color is higher in the periphery than in the center of the retina at both illuminations.
2. The limen of color is higher at decreased illumination than at standard illumination.
3. The direct effect upon the intensity of the sensation produced by decreasing the illumination is shown by the limen determinations to be inconsiderable. In the central retina, the difference is but 1° or 2° . In the peripheral retina at the points considered there is a difference of from 10° to 20° .

Table XXI shows the color limens at both standard and decreased illuminations when white and black screens are used, at the fovea, and at points 15° , 25° , and 30° in the horizontal meridian on the temporal side.

Table XXII has been compiled from Tables XX and XXI to show how much greater the limens were for white and black screens at decreased than at full illumination; how much of the effect may be ascribed to the reduction of the amount of colored light coming to the eye; and how much to the increased induction of the screens. It will be seen from the results of this table that the loss of the sensation in intensity due to the increased brightness induction is much greater than that caused by the reduction in the amount of colored light coming to the eye.

It was shown in Table XIV that quite a great deal of brightness induction is caused by the change in brightness relation between color and screen produced by decreasing the illumination. Table XIX shows how much this induction narrows the limits of sensitivity to the four colors used. Table XXIII, shows how much the limens are raised when the illumination is decreased by the inductive action caused by the change in the brightness relation between stimulus color and gray screen of the brightness of the color at standard illumination.

TABLE XXII.

A. Showing how much greater the limens were with white and black screens at decreased than at standard illumination and how much of this effect may be ascribed to the reduction in the amount of colored light coming to the eye and how much to the increased inductive action of the screens.

Stimulus	Point on horizontal meridian at which limen was taken	White screen		Black screen	
		Total amount greater	Amount due to decrease in amount of colored light coming to eye	Total amount greater	Amount due to decrease in amount of colored light coming to eye
Yellow	0°	7°	2°	12°	2°
	15°	28°	10°	23°	10°
	25°	45°	5°	50°	5°
	30°	75°	15°	63°	15°
Green	0°	5°	0°	10°	0°
	15°	9°	1°	16°	1°
	25°	35°	10°	180°	10°
Red	0°	11°	2°	5°	2°
	15°	26°	4°	12°	4°
	25°	38°	8°	18°	8°
	30°	305°	20°	33°	20°
Blue	0°	13°	1°	3°	1°
	15°	30°	3°	7°	3°
	25°	48°	3°	13°	3°
	30°	70°	20°	40°	20°

TABLE XXIII.

A. Showing how much the color limens were raised at decreased illumination by the induction of the screens which matched the color at standard illumination.

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen with screen of brightness of color at decreased illumination	Limen with screen of brightness of color at standard illumination	Amount limen was raised by change in brightness relation between stimulus and screen caused by decrease of illumination
Yellow	0° 15° 25° 30°	20° 32° 40° 65°	20° 32° 40° 116°	0° 0° 0° 51°
Green	0° 15° 25°	20° 28° 50°	20° 40° 190°	0° 12° 140°
Red	0° 15° 25° 30°	11° 13° 25° 45°	11° 24° 48° 150°	0° 11° 23° 105°
Blue	0° 15° 25° 30°	10° 13° 15° 40°	12° 16° 23° 55°	2° 3° 8° 15°

(D.) *The Influence of Change of Illumination upon the Action of the Preëxposure on the Limens and Limits of Color.*

The brightness of the preëxposure exerts an influence upon the color observation because the eye carries over an after-image from the preëxposure into the color observation. If, for example, the preëxposure is to black, a white after-image is aroused which fuses with the succeeding color sensation and strongly reduces its saturation. The effect of preëxposure is especially strong in the peripheral retina because a very strong brightness after-image is aroused in the peripheral retina by a very short period of stimulation. It is very difficult for the writer to predict from the data she has at hand with regard to the effect of change of illumination upon the sensitivity of the

peripheral retina to the brightness after-image just what will be the effect of change of illumination upon the action of pre-exposure on the color sensitivity of the peripheral retina. But even though there be no change in the sensitivity of the peripheral retina to the brightness after-image with change of illumination, it is obvious that there will be some effect of the change of illumination because of the change in the brightness relation of the preëxposure card to the colored stimulus. In case the stimulus light is gotten by reflection from pigment surfaces, this change of brightness relation is due to the shift in the brightness of the colors produced by the change in the illumination. In case transmitted light is used as stimulus, the brightness of the stimulus color is independent of changes in illumination and will remain constant; but a change in the brightness relation of stimulus to preëxposure will occur because the pre-exposure will lighten or darken with change of illumination. The writer hopes to make the quantitative investigation of this point the subject of a future study. At present she can only point out that if a guarantee is wanted that the effect of the brightness of the preëxposure is eliminated from the results of the observation, the preëxposure must be to a gray of the brightness of the color and the illumination of the room must be kept constant.

The foregoing results show how strongly the changes in the illumination of the visual field influence the color sensitivity of the peripheral retina, particularly when the stimulus is surrounded by a white field. They also show that the influence of surrounding field can not be eliminated even by means of a campimeter screen of the brightness of the color unless some means be had of keeping the general illumination of the room constant. It is obvious without further comment how important it is that a method be devised to standardize this factor. The preceding experiments indicate that without this standardization, no experiment can be repeated from time to time under the same conditions relative to any one of the brightness factors that influence color sensitivity. Results thus obtained are far from comparable.

E. Methods of Standardizing These Factors.

We have shown in the preceding analysis of the color observation that the factors which influence the limits of color sensitivity, and which, therefore, require standardization, are the brightness of the surrounding field, the brightness of the pre-exposure, and the general illumination of the retina. Standard conditions require either that the influence of a factor be eliminated, or that it be reduced to a constant. We have been able to treat all three of these variable factors in one or the other of these two ways. The effect of preëxposure and campimeter screen has been eliminated and methods of measuring the general illumination and of keeping it constant have been provided.

As we have seen, the surrounding field influences the color sensation by adding brightness to the stimulus by induction. When, for example, the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness, the induction takes place in different amounts for the different colors. This white in proportion to its amount reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. The influence of pre-exposure is even more important than of surrounding field. If the preëxposure is to black, white is added as after-image to the stimulus color. The effect of a black preëxposure upon the stimulus color is greater than the effect of a black surrounding field because more white is added as after-image of preëxposure than is induced by contrast from the surrounding field. Now, since brightness induction is greatest when there is maximal opposition between the inducing and induced fields, and since the brightness after-image also is most intensive when there is maximal opposition between the stimulus and the projection field, it is evident that no one screen nor preëxposure can be found that will influence each color by an equal amount. The black preëxposure and surrounding field concomitant upon work in the dark-room can be considered no exception to this statement. The influence of preëxposure and surrounding field can not be successfully eliminated in work in the dark-room. By

using one screen and preëxposure standard conditions of contrast induction and brightness after-image can be maintained only if the colors are made of equal brightness. The objections to this procedure were pointed out in an earlier section. There remains the alternative of choosing in each case gray papers of the brightness of the colored stimulus for the screen and the preëxposure. This necessitates changes of screen and of preëxposure for each stimulus, but insures the complete elimination from the color excitation of all brightness influence due either to preëxposure or to stimulation of the surrounding retina. In this way alone, then, may a proper regulation of these factors be obtained for any investigation whatsoever of the sensitivity of the peripheral retina. Further, the method gives a proper basis with regard to these two important factors from which to start all investigations of the effect of achromatic conditions upon color sensitivity.

Standardization for either one of these factors, however, can be accomplished for one degree of illumination only. As the general illumination changes, the relation of the brightness of the preëxposure and of the surrounding field to the brightness of the colored stimulus changes.⁴⁷ It is obvious, then, that if standardization is to be accomplished with regard to the influence of either of these factors, some means must be devised of maintaining the general illumination of the retina constant.

In order to obtain a standard illumination, two things are necessary: (a) A means of controlling the illumination must be provided, which is sufficiently sensitive to cause small changes. (b) A method of measuring the illumination produced has to be devised; at least, a means must be secured for determining when an illumination has been obtained that is equal to a given preceding illumination. We shall first discuss the method of measurement we adopted. As stated earlier in our paper, no

⁴⁷ When the colored light used to stimulate the retina is independent of the general illumination, e.g., when it is obtained from the spectrum, from monochromatic sources, or from standard filters, these two factors alone will modify the result of the color observation. If, however, light reflected from a pigment surface be used as stimulus, a change in the illumination will in addition change the amount of colored light coming to the eye.

satisfactory means of determining the amount of daylight illumination in a room has been provided by the physicist, so there is little hope at this time of solving the problem from that side. The brightness induction of the peripheral retina, however, has been found by us to be extremely sensitive to changes in the general illumination. This phenomenon seems to provide us with a sensitive measure of these changes, while, at the same time, it represents the combined effects for sensation of the principal subjective factors that might vary from day to day. To apply the method in its most sensitive form, the inductive power of white was chosen because it is the most strongly affected by illumination changes. For example, when No. 14 Hering gray was used as stimulus and white as campimeter screen, a noticeable change was produced in the induction when the white curtain of the optics-room was pulled forward 1 cm. from a position in which its edge was directly above the long axis of the campimeter. This caused a change in the illumination of the room so small that it could not be directly sensed. Further, at 11 o'clock in the morning of a bright day in September, when a point at 25° on the nasal meridian was stimulated, Observer *A* reported that the white screen induced black across the stimulus No. 14 gray to an amount that caused it to equal in brightness 107° of black and 253° of No. 14 gray; at 2 o'clock of the same day the induction was increased until the No. 14 gray matched 150° of black and 210° of the gray; at 4 o'clock of the same day the No. 14 gray matched 180° of black and 180° of the gray.⁴⁸ Working at 25° in the temporal meridian, this observer reported at different times during one day and on different days, the wide variations shown by the following figures: 283° of black, 225° , 145° , 190° , 238° , etc. Observer *C* reported less induction, but her variations from time to time were equally great. At 25° in the temporal meridian, she found at different times 80° of black, 103° , 160° , 175° , etc. After a careful study of the phenomenon with different screens and with different stimuli, the inductive action of the white screen upon a stimulus of No. 14 Hering gray, at 25° in the

⁴⁸ This increase in the inductive action of the screen caused by the decrease in illumination, was accompanied by a shrinkage of the zones sensitive to color covering an area of 4 to 6°.

temporal meridian, was found to provide the best means of detecting changes in the illumination of the optics-room. At this point on the retina, the induction was by no means minimal, nor was it sufficiently great to cause the medium gray chosen for our stimulus to appear too dark to give a small j. n. d. of sensation.

The sensitivity of this method of detecting changes in the general illumination was compared with the sensitivity of the Sharpe-Millar portable photometer. In this photometer one of the comparison fields is illuminated by the light of the room and the other by a standard tungsten lamp enclosed in the photometer box. When the room is illuminated by daylight, the field receiving the light of the room is seen as white, while the field lighted by the tungsten lamp appears as a saturated orange. The difference in color between the two fields renders the photometric judgment difficult and makes the instrument very insensitive for daylight tests. For example, our tests showed that by the method for indentifying an illumination described in the text, a change in illumination could be detected which was produced by drawing the white curtain 1 cm. from a position in which its edge was directly above the long axis of the campimeter. But with the receiving surface of the portable photometer in precisely the same position as the stimulus screen of the campimeter, the edge of the curtain had to be moved 11.3 cm. in order that the change of illumination might be detected. Moreover, this amount of change could be detected only in case the photometric field was continuously observed while the curtain was being drawn, in which case the comparison field was observed to become slightly darkened. The judgment was made, then, in terms of a just noticeably different brightness of the field which was illuminated by the daylight, rather than in terms of a disturbance in the brightness-equality of the two fields. When, on the other hand, the judgment was made in terms of a just noticeable disturbance in the equality of the two fields, as the judgment would have to be made if the photometer were to be employed for the reproduction of any former illumination taken as standard, the curtain had to be drawn 44.2 cm. before the change could be detected. This j. n. d. represents an amount of illumination equal to 2.5 foot-candles.

The next step was to procure a means of changing the illumination of the room by very small amounts. This was accomplished by drawing the white curtain (described p. 86) across the skylight above the apparatus. The drawing of this curtain several inches made little difference in the illumination directly observable by the eye, although, as we have said, a change of 1 cm. when the edge of the curtain was directly above the apparatus, produced a noticeable change in the inductive action of the white screen.

Having thus provided ourselves with a means of producing

small changes of illumination and with a method of detecting them, we had in order to complete our work but to choose an illumination for each observer, which could be taken as standard. Since we wished to work on both light days and days of medium darkness, an average had to be chosen as our standard from the measurements obtained on a number of days ranging from light to dark, so that on bright days the room could be darkened, and on dark days it could be lightened until this value was obtained. For Observer *A* an illumination was selected which caused an induction of black across No. 14 gray stimulus viewed at 25° in the temporal meridian to an amount which caused the gray stimulus to equal in brightness 210° of black and 150° of No. 14 gray; for Observer *B* 180° of black and 180° of No. 14 gray; and for Observer *C* 145° of black and 215° of No. 14 gray. The amount of black induction was identified in each case by means of a measuring-disc made up of sectors of black paper and No. 14 gray of the Hering series.

Previous to each series of observations the illumination of the room was changed until the amount of brightness induction was brought to the value chosen as standard. It was tested at intervals during the sitting and was readjusted when necessary. Details of the method of doing this are as follows: When the white screen and the No. 14 gray stimulus had been put in place, the observer took his position and adjusted the fixation-knot in front of the motor for the 25° point on the temporal meridian. The measuring-disc set at the standard value was mounted on the motor. The observer reported whether the stimulus appeared lighter or darker than the measuring-disc, or of a brightness equal to it. If the judgment lighter or darker was given, the curtain was drawn one way or the other until the stimulus accurately matched the measuring-disc in brightness.

This method not only gives a sensitive measure of the changes of illumination of the visual field and a successful means of standardizing the illumination of a room by daylight, but it has in addition advantages for work in psychological optics not possessed by an objective standardization, could that be successfully obtained. The problem of standardization, includes more for the

psychologist than it does for the physicist, for the former has variables to take into account in addition to the changes that may take place in the energy of the stimulus. Even though the illumination of the room be made objectively constant, we should expect variations in the response of the retina to this illumination because of its own changes from time to time. Brightness contrast, for example, might be expected to vary from sitting to sitting even when the stimulus conditions are kept absolutely constant. Two factors would be concerned in these variations: changes in the inducing power of the surrounding parts of the retina, and changes in the sensitivity of the local area. These changes would take place even when the usual precautions known to the experimenter in this field have been observed. Such precautions are commonly limited to fatigue, adaptation, etc. These precautions do not provide for the changes that occur in the retina from day to day. Moreover, they do not adequately guard against a change in a factor, unless some measure of that factor be had. So far as the writer knows, in these general precautions intended to keep the state of the retina constant, no measure of the variable factor has been provided to test the adequacy of the method. The method proposed by us, however, is planned with this in view. It takes into account not only the objective, but the subjective variables, and reduces both to a constant. For example, when No. 14 gray surrounded by the white field is made equal to the measuring-disc composed of 210° of black and 150° of the No. 14 gray for Observer *A*, it means that the observation may be begun with the assurance that the total result of all the factors—the illumination of the room, the local sensitivity of the retina, and the inductive action of the surrounding parts of the retina—is the same as in the preceding observation.

What has just been said should not be considered as more than a general statement of the application of the principles of the method. In actual practice a greater refinement of working may be attained. If, for example, one wishes to use a preëxposure differing in brightness from that of the colored stimulus, and doubts whether a test which covers only the local sensitivity of the retina and the inductive action of the surrounding parts is a

sufficient check upon the after-image sensitivity, he may make his standard include the effect of the preëxposure he wishes to use. In short, if he does not consider adequate the more general test we have described, he may duplicate, in establishing his standard, any combination of brightness factors, due to preëxposure, brightness of screen, or what not, that he may wish to use in his experiment proper.

The test of a method is how well it works. The test of this method is that we shall be able closely to duplicate our results from sitting to sitting regardless of the changes in the outside illumination from day to day or from morning until afternoon. The method stands the test. Long series of observations in the peripheral retina show a very small M. V.:—much less even than is shown in the ordinary color observations in the central retina where, as compared with the peripheral retina, the factors extraneous to the stimulus exert little influence.

The following table has been compiled from a number of observations to show the variations in the results of color limens and color limits (*a*) when the general illumination was controlled according to the method described above, and (*b*) when no further precautions were observed than were used by previous investigators. In previous investigations of the color sensitivity of the peripheral retina, care has been taken to work only at the same hours of days that appeared equally bright, or, if on days of different brightness, to make a rough approximation of preceding illuminations by means of curtains without using either a definite standard or means of measuring. For our work with the illumination controlled, the gray of the brightness of the color at the illumination selected as standard was used for the preëxposure and the campimeter screen. For the work without any especial control of the illumination, the gray of the brightness of the color on one of the days selected as typical was used throughout for preëxposure and screen. This gave in the first case complete elimination of the effect of preëxposure and surrounding field, and in the second case elimination as complete as could be gotten without accurate control of the general illumination. Results are given in the table for blue and green only because the sensitivity to these colors is affected most by changes of illumination.

Stimulus	Illumination	Screen and Preexposure	Variation of limits on different days	Variation of limens on different days
Green	Controlled	Gray no. 8	0°	0° ⁴⁹
	Uncontrolled	Gray no. 9	4°-6°	60°-82° ⁵⁰
Blue	Controlled	Gray no. 28	0°	2°-3°
	Uncontrolled	Gray no. 30	4°-5°	18°-30°

At the conclusion of a piece of work the object of which has been the elimination of sources of error in one of the oldest and best developed fields of psychological investigation, the following comments having a more general application to other fields in which sensory determinations are required, may be justified. In all sensory determinations, investigators have been very much annoyed by the magnitude of the mean variation that has occurred in their results. This may be due to two sets of factors: errors in the control of the factors that influence the response of the sense-organ, and errors in judgment. To eliminate the latter source of errors, the psycho-physical methods have been devised. Before beginning her attempts to get a better control of the factors that influence the color sensitivity of the retina, the writer had used all the psycho-physical precautions known to her to eliminate errors in judgment, still her inability to reproduce her results rendered in her judgment any accurate investigation of the sensitivity of the peripheral retina hopeless. On the other hand, however, with the control she has been able to get of the factors that influence the sensitivity of the retina to color, and with only a casual observance of psycho-physical precautions, a very close reproduction of results has been rendered possible. With regard to work in the optics of color at least, then, she is forced to conclude that the major source of error is not in the factors that influence the judgment but in those that influence the response of the sense-organ. Moreover, she would suggest that if in other sensory fields more attention were paid to the factors

⁴⁹ The limen for green was taken in both cases at 25° on the temporal retina.

⁵⁰ The limen for blue was taken in both cases at 40° on the temporal retina.

that influence the response of the sense-organ and relatively less to the factors that influence the judgment, a higher degree of precision may be attained in our methods of working.⁵¹

⁵¹ For a further discussion of this point, see Ferree, C. E., Transactions of the Illuminating Engineering Society, 1913, VIII.

THE FLUCTUATION OF LIMINAL VISUAL STIMULI OF POINT AREA

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I. Introduction

In a series of articles published 1906-08,¹ the writer reported the results of an experimental study of the phenomena usually attributed to fluctuation of attention. These phenomena, it was claimed, belong to three sense fields: visual sensation, auditory sensation, and cutaneous sensation. The problem was raised, it will be remembered, in 1888 by Nikolai Lange,² who gathered together the instances of intermittence of minimal sensations and found for them a common explanation in the conception of an instable or fluctuating attention. The recurrent changes in the limen of sensation producing the intermittence are, he contended, due to involuntary changes in the degree of attention given to the stimulus. Previous to the series of articles mentioned above, two other explanations had also been given: (a) Involuntary changes in the adjustment of the sense organ in case of vision and audition, primarily accommodation in case of vision (Münsterberg,³

¹ C. E. Ferree: An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, *Amer. Jour. Psychol.*, XVII., 1906, 81-120; The Intermittence of Minimal Visual Sensations, *Amer. Jour. Psychol.*, XIX., 1908, 59-129; The Streaming Phenomenon, *Amer. Jour. Psychol.*, XIX., 1908, 484-503.

² N. Lange: Beiträge zur Theorie der sinnlichen Aufmerksamkeit und der activen Apperception, *Philosophische Studien*, IV, 1888, 389-422.

³ Hugo Münsterberg: Schwankungen der Aufmerksamkeit, *Beiträge zur experimentellen Psychologie*, Freiburg, 1889, 69-124.

Heinrich,⁴ and Heinrich and Chwistek);⁵ and (b) an overflow of excitation from the circulatory and respiratory centers in the brain (Münsterberg,⁶ Lehmann,⁷ Slaughter,⁸ Taylor,⁹ etc.).¹⁰

In the series of articles mentioned above it was shown on the negative side that in case of vision at least, intermittence cannot be ascribed to any of the previously mentioned causes; and on the positive side that it is a phenomenon of the adaptation and recovery of the sense organ. Intermittence was denied in case of minimal cutaneous sensation,¹¹ and the

⁴ W. Heinrich: Die Aufmerksamkeit und die Funktion der Sinnesorgane, *Zeitsch. f. Psychol.*, XI., 1896, 59-76; and Ueber die Intensitätsänderungen schwacher Geräusche, *ibid*, XLI., abt. 2, 1907, 57-59; Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke, *Bulletin International de l'Academie des Sciences de Cracovic*, Nov., 1898, 363-382.

⁵ W. Heinrich und L. Chwistek: Ueber das periodische Verschwinden kleiner Punkte, *Zeitsch. f. Psychol.*, XLI., Abt. 2, 1907, 59-74.

⁶ *Loc. cit.*

⁷ Alfred Lehmann. Ueber die Beziehung zwischen Athmung und Aufmerksamkeit, *Philosophische Studien*, IX., 1894, 66-95.

⁸ J. W. Slaughter: The Fluctuations of the Attention in Some of their Psychological Relations, *Amer. Jour. Psychol.*, XII., 1901, 313-334.

⁹ R. W. Taylor: The Effect of Certain Stimuli upon the Attention Wave, *Amer. Jour. Psychol.*, XII., 1901, 335-345.

¹⁰ Münsterberg ascribed to this overflow, in case of respiration, an effect on the muscular control of the eye. During inspiration there was more accurate control of fixation and accommodation and during expiration a less accurate control of these adjustments. Lehmann leaves us in some doubt as to just how he believes the effect is produced. He says (*op. cit.*, p. 84): "Wir sahen dass die Reactionen am häufigsten sind in der Nähe des Inspirationsmaximums. Hier ist eben der Blutdruck am grössten, und von diesem Zustand muss angenommen werden, dass er für die psychologische Arbeit des Gehirns günstig sei. Wir wissen ja, dass das Blut, während der Arbeit irgend eines Organes, demselben reichlicher zufließt. Deshalb ist es höchst wahrscheinlich, dass auch die Arbeit eines Organes erleichtert werde wenn durch irgend eine Ursache eine Vergrößerung des Blutzuflusses herbeigeführt wird." Slaughter and Taylor are inclined to believe that the overflow affects the sensory cells directly. In their experiments a plethysmographic record of the peripheral blood pressure was taken while the fluctuations of the visual stimulus were being observed. They conclude that their results show a coincidence between the maxima of the plethysmographic curve and the phase of visibility of the fluctuation record. Two kinds of maxima are found in the plethysmographic tracing, one due to inspiration and the other forming the crest of a long vaso-motor wave of unknown cause, commonly called the Traube-Hering wave.

¹¹ In 1907 the experiments in cutaneous sensation were repeated by Geissler (L. R. Geissler: Fluctuation of Attention to Cutaneous Stimuli, *Amer. Jour. Psychol.*, XVIII., 1907, 318-321). A mistake

phenomenon was left open for further consideration in case of auditory sensation. A part of the work done at this time still remains unpublished. Some of it covers points still in dispute. For that reason two articles will be added to the former series. The first is in answer to an article by Heinrich and Chwistek entitled: "Ueber das periodische Verschwinden kleiner Punkte,"¹² and is intended to clear up, if possible, at least so far as the writer's work is concerned, the last point in dispute between the adaptation and accommodation theories. Heinrich and Chwistek maintain that the fluctuation of minimal visual stimuli of point area is caused by periodic changes in the curvature of the crystalline lens and offer their results for stimuli of point area as evidence that the fluctuations of stimuli of all areas are caused by changes in accommodation. In one of the former studies¹³ the present writer had worked with stimuli ranging from 2 mm. x 2 mm.—42 cm. x 38 cm. in area. He found that stimuli of these areas fluctuate just as readily for aphakial as for normal subjects, and that changes in accommodation, therefore, can not be considered an essential factor in the production of the phenomenon. It had never occurred to him to work with stimuli of point area. In the present study, however, stimuli

was made by him in interpreting the writer's method of stimulating the tongue electro-cutaneously that has not yet been corrected. He says, "In repeating Ferree's experiment with electro-cutaneous stimulation of the tongue, we found some difficulty in eliminating the touch, pressure, and taste sensations set up by the electrodes. The best results were obtained by applying a 1% solution of cocaine to the fore part of the tongue, upon which two strips of tin foil (Christmas tree foil), hammered as thin as possible, were laid. The strips were connected with the interruptor of a Du Bois-Reymond induction coil." Christmas tree foil was not used in the original experiments. This material was rejected at once by the present writer as unsuitable. It is much too stiff and gives rise to pressure sensations. Narrow strips of very thin and pliable wrapping foil were used instead. When these were placed on the fore part of the tongue moistened with spittle, the observer was utterly unable to tell whether or not they were in contact with the tongue when the coil was not working. Neither did they under the action of the current give rise to taste sensations. Of the two procedures the writer would prefer the one used in the original experiments. It seems to him obviously better to make the electrodes of wrapping foil than to use the stiffer material and cocaine the tongue into insensibility to contact, more especially since Geissler's observers report that the cocaine itself sets up distracting sensations in the tongue.

¹² W. Heinrich and L. Chwistek: *Zeitschr. f. Psychol.*, XLI., 1907, 39-74.

¹³ See An Experimental Examination of the Phenomena Usually Attributed to Fluctuation, 98-108.

of point area have been used. From the results of this study it will be shown that the fluctuations of these stimuli present no especial case; for (a) they occur just as readily for aphakial subjects as for subjects with normal eyes; and (b) identified by the tests used by the writer in his earlier experiments they correspond just as closely to adaptation phenomena as do the fluctuations of stimuli of larger area. In the second paper, work on the fluctuation of auditory stimuli will be reported. In this work the writer has succeeded in getting conditions under which no fluctuations occur, whether the stimulus be tone or noise. His results also enable him to explain without recourse to central factors or the tensor mechanism of the middle ear the fluctuations which do occur under experimental conditions different from those he has used. The completion of these two pieces of work rounds up, so far as the writer knows, all of the outstanding points in his case against fluctuation of attention in its original meaning.

II. The Accommodation Theory

That involuntary changes in accommodation are a factor in causing the fluctuation of minimal visual stimuli was proposed first by Münsterberg in 1889.¹⁴ Münsterberg held that the fluctuation of these stimuli is due to two causes: unsteadiness of fixation and involuntary changes in accommodation. Although different views may be held with regard to the essential physiological and psychological factors in attention, all must agree, he says, that when a visual stimulus is attentively observed the eye is fixated and accommodated so as best to receive the impression on the retina. But this adjustment cannot be uniformly maintained for any length of time. Involuntary changes both in fixation and accommodation occur. These changes weaken and confuse the light impression received on the retina, hence an object just noticeably different from its background will alternately disappear into this background and become distinct from it.

The effect of lapses in accommodation is too obvious, he thinks, to need special explanation. The rays of light are no longer sharply focused on the retina and the image of the object blurs and becomes indistinguishable from its background. For unsteadiness of fixation, however, the case is not quite so clear. The explanation is as follows. Fick, Kirschmann, and others have shown that the sensitivity of the retina to colorless light attains its maximum at a certain

¹⁴ Hugo Münsterberg: *Schwankungen der Aufmerksamkeit, Beiträge zur experimentellen Psychologie, Freiburg, 1889, pp. 69-124.*

distance from the fovea. Thus when the eye loses its fixation, the image of the object fixated travels towards a more sensitive part of the retina. This will cause the image of the rings on the Masson disc, for instance, which in the traditional fluctuation experiment are made just noticeably darker than their background, to lighten and become equal in brightness to the background. This gives the phase of invisibility. When fixation is regained, however, the ring again becomes noticeable. This gives the phase of visibility. These two factors, then, the lightening of the image of the ring due to involuntary changes of fixation and the blurring of its outlines due to involuntary changes in accommodation, should, according to Münsterberg, be considered as the cause of the alternate appearance and disappearance of the rings on the Masson disc which were attributed by Lange to fluctuation of attention. Since the writer has already shown in his first article¹⁵ that involuntary changes in accommodation cannot be considered as an essential factor in these fluctuations,¹⁶ space will be taken here only to point out that changes in fixation should also not be considered essential factors in the sense in which Münsterberg considers them factors. In the first place they could, in any event, have an effect only in case the stimulus was darker than the background. If the stimulus were lighter than the background, the brightening of the image would make it stand out more distinctly from the background than before, instead of causing it to disappear into the background as it is observed to do in fluctuating. Moreover, the explanation can have little or no application to the fluctuation of colored stimuli. Since both of the latter classes of stimuli fluctuate just as readily as the former, the principle can be regarded as having little value for purposes of explanation. And in the second place, this factor could not in all probability even cause the fluctuation of stimuli darker than the background, for the increased sensitivity of the extra-foveal retina would not only cause the ring to brighten, but also the background immediately surrounding it. The effect of the factor would

¹⁵ See *An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention*, pp. 84 and 94-96.

¹⁶ In the original article stimuli ranging in area from 2 mm. x 2 mm.-38 cm. x 42 cm. were used. For the writer's observers fluctuations never occurred when a stimulus 38 cm. x 42 cm. or larger was observed at a distance of 1 meter. In the experimental portion of the present paper it will be shown that changes in accommodation are not an essential factor in the fluctuation of stimuli of smaller area than 2 mm. x 2 mm., namely stimuli of point area. Thus with the present paper the demonstration will have been finished for the whole range of areas for which fluctuation occurs.

thus be merely to raise both the gray of the stimulus and of the background in the brightness scale, not to make them equal, unless indeed one were affected more than the other by an amount that would be noticeable in sensation, which can hardly be possible since the difference between them is, to begin with, only just noticeable.¹⁷

Münsterberg supported his explanation by the following experimental evidence. The norm of the period of fluctuation was established for each of his subjects and the following variations of conditions were made. (1) A "prismatische Lorgnette" which moved the field of vision slightly to one side was placed before the eyes. When this was held steadily in position, the period of fluctuation was affected very little, but when it was removed and interposed every 2 seconds, causing the eye to move quickly to the side to follow the shift in the object fixated, the period was very noticeably lengthened. (2) Involuntary blinking was caused every 2 seconds by means of a sharp sound. Fluctuation was prevented. When the eyes were closed voluntarily every 2 seconds, the same results were obtained. This, Münsterberg thinks, was because of the relief of muscular strain produced by the blinking. That is, as the lids are closed, the eyes move downwards and inwards; as they are opened, upwards and outwards (Bell's phenomenon). This frequent relief from the strain of fixating and accommodating so freshens the muscles, he thinks, and improves their action that disappearance never ensues. (3) The whole apparatus bearing the Masson disc was slowly moved back and forth, up and down, and sidewise. Each movement was executed in 2 seconds. Thus, in order to fixate the moving stimulus, the eye was kept continuously moving. The accommodation was also kept continuously changing. In a companion series of experiments the head was moved slowly from side to side. In this case also, in order continuously to fixate the stimulus the eye was compelled to move.¹⁸ Fluctuation did not occur in either series of experiments. Again Münsterberg thinks fluctuation was prevented because the muscles were kept in such a fresh condition that accurate fixation and accommodation could be maintained throughout the observations. A moment's reflection will show (1) that these assumptions cannot be wholly true. The attempt of the eye to follow the moving stimulus, whether the movement was apparent, produced by the interruption of the "prismatische Lorgnette" or actual, produced by the moving of the apparatus bearing the stimulus, must have resulted in the image falling now to this side, now to that side of the fovea. If so, the fixation maintained was far from accurate.¹⁹ Likewise when fixation was lost in blinking, it was doubt-

¹⁷ If, for example, one were very much lighter or darker than the other, the greater sensitivity of the extra-foveal retina might affect one more than the other enough to cause a noticeable change in the difference between them, but this can scarcely be assumed to be the case when one is only just noticeably different from the other.

¹⁸ The movement was equal in amount to the movement of the head and in the opposite direction.

¹⁹ This frequent shifting of the image from the position previously occupied by it on the retina would give abundant chance for the adapting retina to recover, and thus in terms of the adaptation theory to explain the absence of fluctuation.

less regained through a series of small oscillatory movements as commonly happens before the eye comes to rest in taking a new position. And (2) even were the assumptions true, the argument is not at all differential for Münsterberg's theory. The same effect on fluctuation would be expected in terms of the adaptation theory. An abundant reason was given for the stimulus never disappearing in the effect of the eye-movement on restoring the adapting retina. Eye-movement, it will be remembered, exerts its effect on adaptation in two ways. There is (a) an indirect effect. As the result of the movement the image falls on a fresh area of the retina and the area previously stimulated is given a chance to recover. (b) There is a direct effect which is much greater than the indirect effect, namely, the influence of eye-movement upon the amount and direction of the lymph streams that are continually moving hither and thither in the retina. A detailed discussion of this effect was given in the writer's earlier work.²⁰ Eye-movement is thus an essential factor in both theories. The relation to fluctuation ascribed to it in the two theories, however, is very different. In Münsterberg's theory, eye-movement helps to cause the disappearance of the stimulus, while in the adaptation theory it is the most important cause of the reappearance of the stimulus. With regard to the relative merits of these two views, the writer will say that a few minutes' observation of a liminal stimulus should be enough to convince anyone that a voluntary eye-movement, for example, instead of causing the stimulus to disappear, will on the contrary serve to keep it distinct; and, if it has disappeared, will cause it to reappear. For a detailed demonstration that involuntary eye-movement acts in the same way and that it is the chief factor in rendering adaptation intermittent, see the writer's earlier articles "An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention," and "The Intermittence of Minimal Visual Sensations."

Münsterberg also conducted a series of experiments in which a comparison was made of the rate of respiration and fluctuation. The results showed that when the respiration was in short quick gasps, the rate of fluctuation was increased; and when it was slow, the rate of fluctuation was decreased. In explaining this result he attributes to breathing an influence on the muscular control of the eye. With the inspiration there is an increase of the muscular control; and with the expiration, a decrease.

The accommodation factor was next taken up by Pace.²¹ Pace compared the fluctuations obtained by his subjects before and after the paralysis of their ciliary muscles by a solution

²⁰ See The Intermittence of Minimal Visual Sensations, *Amer. Jour. Psychol.*, XIX., 1908, 112-129; and The Streaming Phenomenon, *Amer. Jour. Psychol.*, XIX., 1908, 484-503.

In the blinking experiment, in addition to the effect of the accompanying eye-movement, the blinking would have itself produced an effect on fluctuation. That is, the closing of the lid shut off the light coming from the stimulus and gave the adapting retina a chance to recover.

²¹ Edward Pace: Zur Frage der Schwankungen der Aufmerksamkeit nach Versuchen mit der Masson's Scheibe, *Philosophische Studien*, VIII., 1893, 388-403.

of sulphate of atropine, and found no significant difference in his results. He concluded, therefore, that changes in accommodation could not be considered as essential to the phenomenon.

The theory, however, would not down. It was revived by Heinrich, and Heinrich and Chwistek in a series of articles extending from 1896-1907.²² In the article entitled: "Die Aufmerksamkeit und die Funktion der Sinnesorgane," Heinrich establishes the following principles which he considers of importance in explaining fluctuation. (1) When the attention is directed away from optical impressions (a) the lens takes the curvature characteristic of far seeing, and (b) the lines of sight tend towards the parallel position. The demonstration of these principles, however, cannot be considered as having any very direct bearing on the explanation of the phenomenon of fluctuation, for it may very well be conceived that the voluntary direction of attention away from visual impressions would cause changes in the accommodation and fixation of the eye of a magnitude that would be significant, while the involuntary lapses of attention occurring during the prolonged observation of a stimulus would not cause these changes at all. At least for the purpose of explanation of the phenomenon of fluctuation, the demonstration of the former cannot be considered the equivalent of the demonstration of the latter. And (2) when the attention is directed away from all optical impressions, involuntary changes take place in the curvature of the lens. This conclusion is based upon the recurrent changes that take place in the breadth of the pupil and upon the behaviour of images reflected from the anterior surface of the lens. In drawing this conclusion from the first point of evidence, Heinrich obviously assumes a closer connection between the changes in the breadth of the pupil and changes in accommodation than can safely be done. Any one who has studied the reactions of the pupil under a very wide range of conditions can not help but know that this 1:1 correlation does not exist. Moreover, the connection has not been found in a large enough percentage of cases to make it safe, even plausible, to assume that it exists in any situation in which it has not yet been demonstrated. In his second point of evidence, Heinrich does not describe the behaviour

²² W. Heinrich: Die Aufmerksamkeit und die Funktion der Sinnesorgane, *Zeitschr. f. Psychol.*, XI., 1896, 410-431; Ueber das periodische Verschwinden kleiner Punkte, *ibid*, XLI., 1907, 59-74, und Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke, *Bulletin International de l'Academie des Sciences de Cracovie*, Nov., 1898, 363-382.

of the images observed. Apparently, however, the description is supplied in a later paper published in coöperation with Chwistek entitled "Ueber das periodische Verschwinden kleiner Punkte." At least a method of demonstrating changes in the curvature of the lens based on the behavior of the image reflected from its anterior surface is described here. But the validity of this demonstration is strongly open to question. In the experimental section of the present paper it will be shown that it is much more plausible to ascribe this behaviour to involuntary eye-movement than to involuntary changes in accommodation,—that in fact the same kind of behaviour has been described by de Schweinitz²³ and others, in case of the images reflected from the cornea, as one of the common phenomena of ophthalmometry due to eye-movement.

In the article entitled "Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke,"²⁴ Heinrich discusses the effect of variation of intensity, or differences in intensity between the stimulus and its background on the fluctuation of visual stimuli. Marbe²⁵ had found that an increase of intensity increases the phase of visibility, and conversely a decrease of intensity decreases the phase of visibility.²⁶

This, Heinrich thinks, is just what should be expected were the disappearances caused by recurring lapses in the adjustment of the lens. As will be shown in the next section of the present paper, however, these results offer no differential evidence in favor of the accommodation theory. They are just what would be expected in terms of any theory that has yet been advanced to explain the fluctuation of minimal visual stimuli. Heinrich also notes that for one of Marbe's observers the

²³ G. E. de Schweinitz: *Diseases of the Eye*, Philadelphia and London, 1902, p. 739.

²⁴ *Op. cit.*, 366-369.

²⁵ Karl Marbe: *Die Schwankungen der Gesichtsempfindungen, Philosophische Studien*, VIII., 1893, 615-637.

²⁶ Marbe apparently was the first to make any separation of the phase of visibility from the phase of invisibility in drawing his conclusions, and even he did not take any account of the phase of invisibility in making his comparisons. The total times of visibility of his stimuli under the different conditions alone were compared. This tendency to break up the total period of fluctuation into its phases for purposes of comparison was a step in the right direction, but it was little heeded by his successors.

Marbe concludes that neither the fluctuation of the "Schrödersche Treppenfigur" nor the visual sensation is periodic. The phase of visibility of the visual stimulus increases with the increase in the difference in intensity between the stimulus and its background. The length of the period of fluctuation is a function of this increase.

phase of visibility was decreased when the image of the stimulus fell on the paraxial portions of the retina. This also, he says, is just what should be expected were the disappearance caused by changes in the curvature of the lens. So is it also what should be expected were adaptation the cause of the fluctuation, for one of the most conspicuous differences between the phenomena in the central and peripheral retina is the greater rapidity of adaptation in the peripheral retina.²⁷ Again, then, the evidence cannot be considered as differential. Heinrich also takes into consideration in this paper the results of Pace with the atropinized eye. He claims that changes in the curvature of the lens may still be observed when atropine has been used to paralyze the muscles of accommodation. While the present writer by no means contends that the muscles of accommodation are completely paralyzed by the use of atropine, still he would maintain that Heinrich's claim is strongly open to question if it is based on the kind of observation described by him and Chwistek in the article "Ueber das periodische Verschwinden kleiner Punkte." In any event the point is no longer of importance to the explanation of fluctuation, for it has been shown since that time by the present writer²⁸ that eyes from which the lenses have been removed and which under careful test shown no residual accommodation, get the fluctuation apparently just as readily as the normal eye.

In the article "Ueber das periodische Verschwinden kleiner Punkte," Heinrich and Chwistek, using stimuli of point area, attempt as their *experimentum crucis* to demonstrate the

²⁷ In fact in the writer's own experiments, designed to show the correspondence between adaptation and fluctuation in the peripheral retina, the farther the stimulus was moved towards the periphery of the retina the shorter became the phases of visibility and the longer the phases of invisibility. These experiments were made differential for the adaptation theory (a) by the method of variation of areas, and (b) by showing a rough correspondence between the phase of visibility in the fluctuation experiments with the adaptation time for different visual stimuli from center to periphery of retina. No. 27 gray and the red, green, blue, and yellow of the Hering series of papers were used as stimuli. Only a partial list of the results obtained was published, however, because the writer did not at that time consider the phenomenon in indirect vision worthy of more space. The main arguments were established for direct vision and no more data were included for indirect vision that were needed to show in a general way that the phenomena here present no exception. (See "An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention," 116-119.)

²⁸ See An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, 84 and 94-96.

coincidence of fluctuation and changes in accommodation. Heinrich had mentioned the desirability of making this demonstration in the preceding paper, but had discarded the idea as infeasible because of the conditions under which the experiment would have to be conducted. In choosing to work with point stimuli in this study, Heinrich and Chwistek have admittedly selected the conditions most favorable to the accommodation theory, for by Heinrich's own statement in the explanation of his theory in an earlier paper²⁹ changes in accommodation would be more apt to cause the disappearance of point stimuli than of stimuli of larger area. Notwithstanding this admission, however, the results they get with point stimuli are advanced in the later paper as evidence that the fluctuation of stimuli of all areas is due to involuntary changes in accommodation. Their work with stimuli of point area will be taken up in detail in the next section of this paper.

*III. The Fluctuation of Stimuli of Point Area (the Work of Heinrich and Chwistek)*³⁰

Heinrich and Chwistek maintain that the fluctuation of visual stimuli of point area is caused by periodic changes in the curvature of the crystalline lens. They also offer their results for stimuli of point area as evidence that the fluctuations of stimuli of all areas are caused by changes in accommodation. Four arguments are advanced by them in support of this conclusion. (1) Periodic changes in the curvature of the lens are directly observable. Moreover, these changes are found roughly to coincide with the fluctuations of the point stimulus when both observations are conducted at the same time. They describe two methods of demonstrating this change of curvature. One may be considered popular, the other technical. The popular demonstration may be conducted as follows. Prick two holes in a cardboard nearer together than the breadth of the pupil of the eye. Hold the card close to the eye and look through the holes at a bright light. The holes will be seen as two dispersion circles with a bright overlapping area. When the curvature of the lens changes, the overlapping area alternately contracts and expands. That is, as the lens becomes more convex, the dispersion circles become smaller and the overlapping area becomes narrower; and conversely, as the lens becomes less convex the circles become

²⁹ See *Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke*, 366-67.

³⁰ W. Heinrich and F. Chwistek: *Zeitschr. f. Psychol.*, XLI., Abt. 2, 1907, 59-73.

larger and the overlapping area becomes broader. This change in the overlapping area, they say, can readily be observed. Their technical demonstration was accomplished by means of an ophthalmometer. Their method was as follows. Two spots of light were thrown on the eye of the observer by means of two mirrors reflecting the light from a lamp properly placed with reference to these mirrors and to the eye of the observer. These images were observed by means of an ophthalmometer. Their description of method is extremely meager. They say: "Lässt man die beobachtete Person den Punkt fixieren, dessen periodisches Verschwinden untersucht wird, und dreht die Glasplatten des Ophthalmometers, bis man in dem Instrument die beiden von der vorderen Linsenfläche reflektierten Bildchen als drei Punkte sieht, so offenbart sich jede Krümmungsänderung der Linse dadurch, dass der mittlere Punkt bei grösseren Änderungen sich spaltet, bei kleiner breiter wird. Man beobachtet dann ohne weiteres, dass die Linseneinstellung nicht stabil ist, sondern dass sie kleinen periodischen Aenderungen unterliegt. Diese Aenderung konnte mit unserem Instrument durch die Drehung der Platten um höchstens 0.5° kompensiert werden. Es war uns unmöglich die Aenderungsrichtung aus den Bewegungen des Punktes zu erkennen."³¹ While these changes in the image reflected from the observer's eye were being recorded by a second person, the observer himself recorded the fluctuations of a point stimulus. Simultaneous records were thus obtained which could be compared in order to determine whether the phases of fluctuations coincided with the phases of changes in the image reflected from the eye. The point stimulus consisted of a small black point on a white ground or a small white point on a black ground, 0.1-0.3 mm. in diameter, observed at a distance of 70-150 cm. Two observers Herr Sk. and Herr Zacz, were used. The eyes of both were normal, or emmetropic. Chwistek recorded the changes in the images reflected from the eye. Their results are stated as follows. For observer Sk., 776 phases were recorded. "Einseitige Notierung vom Herrn Sk., d. h. notiertes Verschwinden des Punktes ohne entsprechend notierte Akkommodationsschwankung ergab sich in 38 Fällen. Einseitige Notierung vom Herrn Chwistek, d. h. notierte Akkommodationsänderung ohne entsprechende Aufzeichnung des Verschwindens des Punktes fand man in 40 Fällen." For observer Zacz, 296 phases were recorded. "Einseitige Notierung vom Herrn Zacz in 31 Fällen. Einseitige Notierung vom Herrn Chwistek in 32 Fällen."

³¹ *Op cit.*, 60-61.

(2) Within the range of areas used by them an increase in the area of the stimulus was found to give longer phases of visibility and shorter phases of invisibility. And, conversely, a decrease in the area of the stimulus was found to give shorter phases of visibility and longer phases of invisibility. Points were observed ranging for one observer (emmetropic) from .2 mm.-.5 mm. in diameter, at distances ranging from 100 cm.-126.5 cm.; for another observer (2.5 myopic), .2 mm.-.5 mm. in diameter at distances ranging from 35 cm.-39 cm.; and for a third observer (4 D. myopic), .2-1.5 mm. at distances ranging from 15 cm.-28.5 cm.

(3) The phase of visibility was also found to vary with the intensity of the stimulus or with the brightness difference between the point and its surrounding field. The greater was this brightness difference, the longer the phase of visibility was found to be as compared with the phase of invisibility, and the less was this brightness difference, the shorter was the phase of invisibility.

(4) When the stimulus was placed just beyond the far point for an observer with myopic eye, it was found to become periodically more and less distinct. Also two points placed at this distance were found alternately to blur into one and to separate into two. Two observers were used in these experiments.

Before passing to his own experimental evidence that involuntary changes of accommodation are not an essential factor in the fluctuation of stimuli of point area, the writer has the following comments to make on the work of Heinrich and Chwistek. (1) In this work they have created for themselves a special problem, that is, they employed stimuli of point area and strongly supraliminal intensity. The fluctuation of such stimuli has never been ascribed to the fluctuation of attention. Historically considered, then, they are not working with the phenomenon to which they primarily make their conclusions apply; and, moreover, they have not in any way shown in a satisfactory manner the propriety of applying their conclusions to the phenomenon explained by Lange as due to the instability of attention. (2) Their popular demonstration of involuntary changes in the adjustment of the lens is strongly open to question. Employing 124 subjects, the writer has not been able to make it work in a single case in which care was taken to rule out extraneous factors which would themselves cause the phenomenon. For example, extreme care must be taken to hold the card steady. Any variation in the distance of the holes from the pupil of the eye will cause a

variation in the breadth of the overlapping area. Especially must care be taken that the card does not touch the lid of the eye, for movements of the ball of the eye and more particularly of the lid change the distance of the card from the eye. These movements are often unnoticed unless the observer is especially looking for them, and are frequently of sufficient range to cause a change in the size of the dispersion circles. Without a doubt the phenomenon, when it has occurred, has been, so far as the writer's experience is concerned, an artifact due to the conditions under which the observations were made. (3) Their technical demonstration by means of the ophthalmometer is, in the writer's opinion, just as strongly open to question. The writer criticizes this demonstration, however, with reluctance because of the meagerness with which they have described their method of working and observations. The following points, however, may be noted. (a) Working as they did, two images should have been observed, one reflected from the cornea, the other from the anterior surface of the lens.³² Both images should have been very much alike, with the exception that the one reflected from the cornea should have been larger and more distinct. Nothing is said in the article, however, that would give evidence to the reader that more than one image was observed, or that the image described was actually reflected from the lens. But even if it were granted that the image observed was reflected from the lens, it would signify little, for the phenomenon described by them could have been caused just as well by involuntary eye-movements as by changes in the curvature of the lens. That is when the eye is accommodated, the anterior surface of the lens is hyperbolic in shape and varies in curvature considerably from point to point. A movement of the eye would, therefore, cause the rays of light forming the image to be reflected successively from points at which the surface had a different curvature. Each difference in curvature would give a difference in the size of the image reflected. Eye-movement would, therefore, produce the same effect in the size of the image as changes in the convexity of the lens. That is, movements of greater range would correspond in effect to the changes in convexity of greater magnitude, and, conversely, movements of lesser range to the changes in convexity of lesser magnitude. In fact, the phenomenon they describe is one of common

³² An image reflected from the posterior surface of the lens might also have been observed. But since this image is inverted and is besides very indistinct, it may be considered as having no bearing on the discussion.

observation in case of the corneal image, and in this case no attempt has been made to ascribe it to recurrent changes in the curvature. For example, de Schweinitz, in his treatise on the diseases of the eye, says:³³ "Nothing is more common than to see the images of the mires [the mires correspond to the lights used by Heinrich and Chwistek] separate and overlap so that the apparent curvature of the cornea seems to change while under observation. The changes are due to slight movements of the eye which bring different portions of the cornea into view." We know that there are many involuntary eye-movements per minute even with the best control of fixation that can be obtained.³⁴ It seems more plausible, therefore, to attribute the phenomenon observed by Heinrich and Chwistek to the involuntary eye-movements which we know occur in abundance, than to use it as a proof of a new phenomenon, namely, the involuntary changes in the curvature of the lens, even if it be granted that the image from the lens was observed. At least, it may be said that Heinrich and Chwistek were not warranted in concluding as they did, without having secured any differential evidence to bear out their conclusion or without even having considered eye-movement as a causal factor. (d) Since the corneal image is known also to double and overlap, a rare opportunity was given to Heinrich and Chwistek, in making these observations, to compare the behaviour of the corneal image with that of the image reflected from the lens, if that really were the image they observed, and to determine by the presence or absence of coincidence in the two sets of changes, whether the doubling and overlapping of the images reflected from the lens has the same or a different cause from the doubling and overlapping of the images reflected from the cornea. Had both images really been observed or had the characteristic doubling and overlapping of the corneal image even been known to Heinrich and Chwistek, one can hardly conceive that their conclusions would have been drawn without recourse to this means of determining whether or not both sets of changes should be ascribed to a common cause. In short, judging from their report as it stands; from the fact that the ophthalmometer as it is ordinarily constructed and used is intended only for the observation of the corneal images, and that such a phenomenon as they describe would

³³ G. E. de Schweinitz: *Diseases of the Eye*, Philadelphia and London, 1902, 739.

³⁴ See C. E. Ferree: An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, *Amer. Jour. Psychol.*, XVII., 1906, 113-115; also The Intermittence of Minimal Visual Sensations, *ibid.*, XIX., 1908, 83-112.

have been extremely difficult to observe in case of an image reflected from the lens; and from the fact that descriptions of similar behaviour on the part of the corneal image are given by other observers, the writer cannot help but think, without any wish to be hypercritical, that considerable grounds are given for suspecting that Heinrich and Chwistek have observed the doubling and overlapping of the corneal image which is commonly attributed by de Schweinitz and others to involuntary eye-movement.³⁵ Moreover, the crux of their argument is that they have actually observed a coincidence between the fluctuation of the visual stimulus and the changes in the adjustment of the lens. This, they contend, gives a certainty to their argument not yet attained in previous work on the problem. But even if the question whether or not it was a lens image that was observed be disregarded, it will be seen from the above discussion that is strongly probable that the coincidence they actually observed was between eye-movement and the fluctuation of the visual stimulus and not between changes in the curvature of the lens and the fluctuation of the visual stimulus.

(4) Their explanation of the effect of variation of area on the fluctuation of a visual stimulus could apply only to stimuli of very small area. Moreover, even in the case of very small areas the effect they got is just what might be expected as the result of increase of area either in terms of Loria's explanation of the fluctuation of stimuli of point area³⁶ or in terms of the writer's explanation: adaptation interfered with by eye-movement. They make two cases of their explanation of how changes of accommodation cause the fluctuation of stimuli of point area: (a) when the stimulus is a black point in a white ground and (b) when it is a white point in a black ground. In the former case the rays of light coming from the margin of the black point are not sharply imaged on the retina when the lens changes focus, hence they spread over the dark space on the retina corresponding to the black point. It is obvious that this spreading of the marginal light could blot out the dark space only in case the black stimulus were of very small area. Hence the explanation could not apply at all to stimuli of the size ordinarily used in the work on fluctuation. In the latter case the rays of light coming from the white point are not sharply imaged when the accommodation

³⁵ The writer leaves himself willingly open to correction on this point, however.

³⁶ See Heinrich and Chwistek: *op. cit.*, p. 60; also Stanislaw Loria: *Untersuchung über das periphere Sehen*, *Zeitschr. f. Psychol.*, XL., 1905, 160-186.

changes, and are spread over the surrounding dark space. Since strongly supraliminal stimuli were used, it is extremely doubtful whether even very small stimuli could be carried below the limen of sensation from this cause. Moreover, because strongly supraliminal stimuli were used and no attempt was made to control the intensity of the stimulus, an increase in the area of the stimulus would function for sensation as an increase of intensity.³⁷ Therefore, from this cause alone, according to the theories advanced either by Loria or by the writer, an increase of area would produce an increase in the phase of visibility. Even in case of stimuli of point area, then, the effect of increase of area described by Heinrich and Chwistek offers no differential argument in favor of the explanation advanced by them. Furthermore, the theory of fluctuation of attention was meant to apply only to stimuli of liminal or approximately liminal intensity. When such stimuli are used, an increase of area produces just the opposite effect. For example, working in 1906 with liminal stimuli ranging in area from $.5 \times .5$ cm. to 15×15 cm., the writer found that an increase of area caused a decrease in the phase of visibility and a corresponding increase in the phase in invisibility. And in the experimental section of this paper it will be shown that the same effect is produced in case of liminal stimuli of very small area. In both of these cases care was taken to keep the stimuli liminal in order that an increase in the area of the stimulus would not produce an increase in the intensity of the sensation. (4) The fourth argument advanced by Heinrich and Chwistek has no differential value whatever. It was first used by Heinrich in 1898, as applied to stimuli of larger area.³⁸ A more intensive stimulus, he thinks, is not so liable to be blotted out by involuntary changes in accommodation. Therefore, he concludes, the more intensive is the stimulus the longer should be the phases of visibility and the shorter the phases of invisibility. It is obvious, however, that this result is just what should be expected from adaptation as a causal factor. It should be expected even were it held that fluctuation is due to instability of attention. In fact an increase in the phase of visibility and a decrease in the phase of invisibility would be the natural consequence of an increase in the

³⁷ We seem to have here a violation of one of the most fundamental principles in experimental procedure, namely, when it is wanted to determine the effect of a given factor, the effect of all other factors should, if possible, be eliminated from the results of the experiment.

³⁸ W. Heinrich: Zur Erklärung der Intensitätsschwankungen eben merklicher optischer und akustischer Eindrücke, *Bulletin International de l'Academie des Sciences de Cracovie*, Nov., 1898, 363-382.

intensity of the stimulus in terms of any theory that has yet been advanced to explain fluctuation.

(5) The writer is in some doubt as to what is meant by the fifth argument. "Beindet sich der Punkt, dessen Verschwinden man beobachtet, innerhalb des Akkommodationsbereiches der Linse, so beobachtet man nur das periodische Verschwinden desselben. Die Verhältnisse sind komplizierter, wenn man den Punkt ausserhalb des Fernpunktes aufstellt was beim myopischen Auge leicht ausführbar ist. In diesem Falle zeigt sich, dass der beobachtete Punkt, der jetzt nicht scharf gesehen wird, periodisch verschwindet, aber auch periodisch schärfer gesehen wird."³⁹ In the first place he cannot understand why the above result should be expected, were changes in accommodation present, for when the far point is actually reached the ciliary system should be completely relaxed. It is difficult then to see how the lens can be allowed to become any flatter, unless indeed it be held that the theory of accommodation commonly accepted for the human eye is incorrect. And in the second place, working under the conditions described by Heinrich and Chwistek, the writer has been unable to get anything that might be called three distinct and separate stages of clearness of his stimulus. Moreover, any stimulus of supraliminal intensity, fluctuating from any cause whatsoever and especially from causes purely retinal, would be apt to have, although not sharply defined, maximum, minimum, and intermediate degrees of distinctness. This the writer's observers were able to get at whatever distance the stimulus was put from the eye, but they were utterly unable to detect the three distinct and separate stages that are reported by Heinrich and Chwistek. Nor were they ever able to see the stimulus as clearly beyond the far point as they were at the far point or nearer than the far point. In short, there was never at this point what could be considered a norm of clearness which was succeeded either periodically or even at irregular intervals by a degree of clearness in excess of this norm. Continuing, Heinrich and Chwistek say: "Das lässt sich am besten durch folgendes Experiment illustrieren: Stellt man nicht weit ausserhalb des Fernpunktes des myopischen Auges als Objekt zwei Punkte, die so nahe liegen dass sie als ein Fleck gesehen werden, so beobachtet man, dass die Punkte periodisch auf kurze Zeiten getrennt erscheinen." The writer has not succeeded in getting this phenomenon when working beyond the far point with the myopic eye. It is, however, of common occurrence for any eye when the points are placed

³⁹ *Op. cit.*, 66.

at or slightly nearer than the limit of clear vision for these points and are regarded for any length of time. The points alternately blur into one and separate into two. In all probability both retinal and accommodation factors are involved in this result, but no definite estimate can be made of how much importance should be assigned to either until comparative records be made for subjects without lenses and for normal subjects. In the writer's opinion, however, the above experiment comes the nearest of any yet described by Heinrich and Chwistek to giving tangible evidence that involuntary changes in accommodation occur. But even to demonstrate clearly that these changes occur, would not prove that they are essential or even important factors in the fluctuation of minimal visual stimuli even of point area.⁴⁰ That they are not essential factors will be shown by the writer in the next section of this paper.

IV. Experimental

In this section of our paper we propose to show (1) that involuntary changes in accommodation are not essential or even important factors in the fluctuation of minimal visual stimuli of point area, and (2) that, identified by tests used by the writer in his earlier experiments, these fluctuations correspond just as closely to adaptation phenomena as they do for stimuli of larger area.

Probably the most convincing proof that one can offer that involuntary changes of accommodation are not essential to the fluctuation of stimuli of point area is the results obtained from aphakial subjects. Observations were made by the writer upon four aphakial subjects. They were all above sixty years of age, and three were above seventy. All of them had had the lenses removed from their eyes from 15-20 years before. Both the advanced age of the subjects and the long period that had elapsed since their lenses were removed favored the absence of any residual accommodation. To make sure of this point, however, they were each tested as follows. The subject's head was clamped in a head-rest and a card bearing letters of very fine print ($3\frac{1}{2}$ point type) was slid along a meter rod supported at the level of his eyes in the

⁴⁰ Lest it be thought that this experiment shows some coincidence between changes in accommodation and fluctuation, it may be pointed out that the cycle of changes experienced by the two points does not even include disappearance. The points merely blur into one and separate into two. That is, the only phenomenon cited by Heinrich and Chwistek that really gives any tangible evidence of involuntary changes in accommodation does not even occur in a series in which fluctuations are found.

median plane. The card was placed at his point of clearest vision as determined by the focus of his glasses and was moved both nearer and farther until just noticeable dimming took place. Every precaution was taken to secure accuracy. For one of the subjects the card could not be moved more than 2 mm. from the point of clearest vision without becoming less distinct. Very little more movement was required for any of the subjects. It may be safely said that all were practically without accommodation. Two of these observers were the same as were used by the writer in the earlier investigations made with stimuli of larger area. Opportunity was thus had to determine whether or not changes in accommodation play a more important rôle in the fluctuation of stimuli of point area than of stimuli of large area. So far as could be told from the records in both cases, they do not play a more important rôle. In cases of stimuli both of large and of very small area, the fluctuations occur for the aphakial subject with apparently no greater variation from the normal subject than is found from individual to individual with normal eyes.

Of the methods used in the former work to demonstrate that fluctuation is a phenomenon of the adaptation of the sense organ, only three were available for stimuli of point area. In the first of these the stimuli were made of different colors. Speaking of this method in the first paper⁴¹ of the former series, the writer says, "Colors and grays were found to have an order of fluctuation times corresponding to their adaptation times. Four colors, red, green, blue, and yellow, gave very different fluctuation periods as compared with each other and with No. 27 Hering gray. The visibility times obtained were in the following order: red, green, blue, and yellow, the yellow being nearly four times as long as the red.

"The complete adaptation times for sheets of the same colors were found to have the same order of length and a rough correspondence as to ratio of length. Further, a striking fact came out with regard to the phases of invisibility. Since red, for example, has a shorter phase of visibility than green, one might naturally expect that its phase of invisibility would also be shorter than the phase of invisibility of green. The reverse, however, is true. Red has a longer invisibility than green, and this peculiarity is especially marked if one considers the proportionality between the phases, *i. e.*, the ratio invisibility: visibility. The same thing is true of the complementaries blue

⁴¹ An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention, p. 86.

and yellow. Clearly, we cannot look for a central explanation of this peculiarity; but it seems just what we might expect of adaptation from the standpoint of the compensation theory. The recovery process for the red is the green process. The green process is longer and seemingly more tenacious than the red, as is shown by the adaptation experiments proper, and is further borne out by the longer duration of the green after-image. A similar relation obtains in the blue-yellow process." In the earlier work, the stimuli were gotten as follows. Squares of the color of the size that was wanted were pasted on a gray of the brightness of the color. The stimulus was rendered liminal by letting the light pass from the colored paper through a sheet of milk glass, matt on one side, placed at such a distance from the color as to render its intensity liminal. The intensity was easily regulated by slight changes in the distance of this glass from the colored paper. The light reflected from the colored papers could not be used, however, for stimuli of point area, because the milk glass mentioned above had to be used to reduce the intensity of the stimulus and it was impossible to get this glass thin enough to give noticeable color with stimuli of point area. Light was transmitted through color-filters instead. The stimulus was gotten as follows. A hole was pricked through a gray cardboard with a fine needle and covered with one or more layers of colored gelatin. In front of the card, in contact with it, was placed the sheet of milk glass, matt on one side. The hole was illuminated by a row of lights placed behind the cardboard, normal to its surface, at a distance sufficient to render the stimulus liminal. By this arrangement a just noticeable point of color was presented to the observer seated in front.

A stimulus given by reflected light has always yielded more differential results in former experiments with the method of colors than a stimulus by transmitted light. This is probably due to the fact that we were able to get from the former type of stimulus more color in proportion to the white light present, thus better bringing out the color differences in the liminal stimuli. The poorer method had to be used, however, because as stated above milk glass with one surface matt could not be obtained thin enough so that a point of colored paper pasted upon a background of equal brightness could be seen through it.⁴²

⁴² In case of the colored papers the liminal stimulus and surrounding field were of the same brightness, because the paper giving the stimulus was pasted on a gray of the brightness of the color. The only effect of the milk glass in front was to change the general scale of brightness of color and surrounding field. No brightness inequality was produced.

The registration of results was secured by means of a Ludwig-Baltzar kymograph, a telegraph key and an electromagnetic recorder, a Jaquet chronograph (set to seconds), and a lamp rheostat to cut down the current from the lighting circuit. All of this apparatus was screened from the observer by means of a sliding curtain. The work was done in a long room with the windows all at one end. Thus cross lights, unequal illumination of the background, etc., could be avoided. The illumination of the room was kept fairly constant by means of thin curtains covering the windows.⁴³ The observer sat with his back to a high window and his head in a head-rest fastened to the edge of a long table, along which the frame bearing the stimulation apparatus was moved as required. The time used throughout was 1 sec. The following results were obtained. As in the earlier work with stimuli of a larger area, red showed a shorter phase of visibility and a longer phase of invisibility than green; and blue, a shorter phase of visibility and a longer phase of invisibility than yellow. In spite of the poorer method we were required to use, the results obtained were almost as strongly marked as they were when the same method was used with stimuli of a larger area. These results have been verified at the time this work was done and since by a large number of observers practiced and unpracticed. The results of three observers chosen as typical will be reported here. Tables I-III have been compiled from these results.

TABLE I

Obs. C.—Fluctuation with stimuli of the four principal colors of point area showing that the phases of visibility and invisibility have the characteristic adaptation and recovery peculiarities of these colors just as they have with stimuli of larger area.

Stimulus	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red	4.36	.79	1.68	.65	2.585	.385	6.04
Green	5.30	.93	1.13	.42	4.690	.213	6.43
Blue	7.75	1.12	1.41	.71	5.496	.181	9.16
Yellow	13.10	1.76	1.32	.59	9.925	.100	14.42

In the case of the stimulus by transmitted light, this result was not so effectively secured because of the greater difficulty of equating the point of light and the surrounding field.

⁴³ To keep the illumination constant presupposes a means of measurement. At the time the writer had at his command no means of measuring the illumination of a room by daylight. For a method of

TABLE II

OBS. G.

Stimulus	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red.	5.1	1.12	1.26	.54	4.047	.247	6.36
Green.	7.43	1.54	1.14	.37	6.517	.153	8.57
Blue.	10.9	1.59	1.46	.52	7.466	.133	12.36
Yellow.	Did not fluctuate at all during period of observation.						

TABLE III

OBS. CA.

Stimulus	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red.	1.82	.59	1.62	.32	1.123	.890	3.44
Green.	2.82	.53	1.27	.36	2.243	.450	4.09
Blue.	4.15	.55	1.70	.35	2.441	.409	5.85
Yellow.	5.22	.86	1.52	.51	3.434	.291	6.74

In the second test strips of colored paper of the breadth of a point and 5 cm. in length were used.⁴⁴ They were pasted on a gray background of the brightness of the color in each case and were observed as liminal color on the matt surface of the milk glass placed in front. They were arranged first with their longer dimension in the vertical plane, then in the horizontal plane. The former arrangement favored a maximal disturbance of adaptation for observers having the greater range and frequency of eye-movement in the horizontal plane, and gave with these observers in the fluctuation experiments a corresponding increase in the phase of visibility and decrease in the phase of invisibility. Conversely, the latter arrangement favored a minimal disturbance of adaptation for these observers and gave a corresponding decrease in the phase of visibility and increase in the phase of invisibility.

doing this, see C. E. Ferree and Gertrude Rand: An Optics-Room and a Method of Standardizing Its Illumination, *Psychol., Rev.*, XIX., 1912, 364-373.

"In this test we were able to use colored paper because strips, although only of the breadth of a point, could be seen when 5 cm. long through the sheet of milk glass we used.

For each observer careful records were made of the frequency and range of movement and the total time the eyes were moving according to the methods described in the former papers.⁴⁵

Speaking of this test in the first paper of the former series, the writer says, pp. 84-90, "A more direct experimental confirmation than was afforded by the method of variation of areas of this view that eye-movement interferes with the course of adaptation and is also the conditioning factor for the wide range of variability found in the phases of visibility and invisibility in the fluctuation experiments, is given by the following results. An examination of average frequency of eye-movement in the horizontal and vertical planes during fixation showed that three of our observers had a marked excess in both frequency and range in the horizontal, while the fourth had an excess of frequency in the vertical, but of range in the horizontal plane. This appeared to mean that for three observers, there was greater change of stimulation, and consequently greater relief for the adapted elements, in the horizontal than in the vertical direction; while the reverse was true, though probably to a lesser degree, for the fourth. To test this interpretation, stimuli longer than broad were used, *e. g.*, slips of paper 5 mm. x 40 mm. When these were placed with the longer dimension vertical, the shorter dimension would fall in the direction of greater unsteadiness of fixation for the three observers who had the excess of eye-movement in the horizontal plane. Consequently, a maximal interference with adaptation for these stimuli would be obtained, and one might expect an increase in the phase of visibility and a decrease in the phase of invisibility. On the other hand, if the longer dimension were placed in the horizontal and the shorter in the vertical plane, the minimal interference possible for these stimuli would be secured, and a decrease in the phase of visibility and an increase in the phase of invisibility should ensue. For the fourth observer with the stimulus arranged as described above, the reverse should be true, but probably not in so marked a degree, since his range was greater in the horizontal, which fact to a certain extent would counteract the effect of frequency. . . . That these methods of arrangements of stimulus caused a marked change in the phases of visibility and invisibility for each

⁴⁵ See *An Experimental Examination of the Phenomena Usually Attributed to Fluctuation of Attention*, 113-115; and *The Intermittence of Minimal Visual Sensation*, 84-87.

observer will be seen by inspecting the Tables. Indeed the correspondence between the quantities : $\frac{\text{Visibility} \div \text{invisibility}}{\text{visibility}^1 \div \text{invisibility}^1}$,

and $\frac{\text{frequency}}{\text{frequency}^1}$, is much closer than was anticipated."⁴⁶

The results for the strips of point breadth are given in Tables IV-VI. For all the observers whose results are given in these tables, both the range and frequency of eye-movement were greater in the horizontal than in the vertical plane.

The third test was based upon the fact that the time required for a colored stimulus to adapt depends to some extent upon the surrounding field.

The question of what is meant by adaptation is logically raised here; among the followers of the Hering theory, it has come to mean, apparently, simultaneous induction, and Aall, reviewing the writer's first article,⁴⁷ assumes that that is what is meant by adaptation in that

TABLE IV

OBS. H.—Fluctuation with horizontal and vertical arrangement of the stimulus. Showing how arrangements that favor maximal and minimal interference with adaptation affect the phases of visibility and invisibility. Stimulus 3 mm. x 50 mm.

Stimulus	Arrangement	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Vertical....	2.95	.64	1.68	.31	1.756	.569	4.63
"	Horizontal..	1.08	.23	2.29	.40	.471	2.120	3.37
Green...	Vertical....	4.04	.72	1.45	.26	2.786	.358	5.49
"	Horizontal..	1.69	.38	1.76	.37	.960	1.041	3.45
Blue....	Vertical....	5.40	.86	2.03	.51	2.660	.376	7.43
"	Horizontal..	2.51	.49	3.10	.46	.806	1.235	5.61
Yellow..	Vertical....	6.99	.97	1.45	.29	4.82	.207	8.44
"	Horizontal..	3.55	.72	2.10	.56	1.928	1.690	5.65

⁴⁶ For a more complete understanding why arranging the shorter dimension of the stimulus in the direction of the greatest eye-movement causes relatively long phases of visibility and short phases of invisibility; and conversely arranging the longer dimension of the stimulus in the direction of greatest eye-movement causes relatively short phases of visibility and relatively long phases of invisibility, see The Intermittence of Minimal Visual Sensations, 112-129; and The Streaming Phenomenon, 484-494.

⁴⁷ *Zeitschr. f. Psychol.*, XLIII., Abt. 2, 1906, 456-457.

TABLE V

OBS. R.

Stimulus	Arrangement	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Vertical....	3.60	.75	1.46	.24	2.548	.405	5.06
"	Horizontal..	1.14	.28	3.40	.75	.335	2.982	4.54
Green...	Vertical....	4.30	.62	1.39	.19	3.093	.323	5.69
"	Horizontal..	2.42	.47	2.36	.37	1.025	.975	4.78
Blue....	Vertical....	4.93	1.08	1.68	.34	2.933	.340	6.61
"	Horizontal..	2.95	.54	4.53	.89	.651	1.535	7.48
Yellow..	Vertical....	6.61	1.23	1.46	.31	4.527	.220	8.07
"	Horizontal..	3.26	.79	2.75	.49	1.189	.843	6.01

TABLE VI

OBS. G.

Stimulus	Arrangement	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Hering gray No. 27	Vertical....	8.48	1.32	2.03	.39	4.177	.239	10.51
"	Horizontal..	3.14	.71	3.21	.56	.978	1.022	6.35
Red....	Vertical....	5.09	1.12	1.84	.29	2.766	.361	6.93
"	Horizontal..	1.65	.38	3.61	.78	.457	2.187	5.26
Green...	Vertical....	7.42	1.29	1.94	.41	3.824	.261	9.36
"	Horizontal..	2.52	.48	2.98	.48	.845	1.182	5.50
Blue....	Vertical....	8.99	1.47	2.84	.39	3.165	.315	11.83
"	Horizontal..	3.88	.84	5.99	.97	.647	1.542	9.87
Yellow..	Vertical....	11.49	1.97	1.90	.32	6.047	.165	13.39
"	Horizontal..	4.84	.97	3.86	.89	1.254	.797	8.70

article. The writer, however, by no means believes that the tendency of a color to lose its saturation on prolonged exposure to the eye or of all grays to become mid-gray is due entirely or even to any considerable extent to simultaneous induction. He grants an influence to the surrounding field when there is a surrounding field, and is at present making a quantitative study of that influence, but it is obvious that the influence of the surrounding field can have no part in the phenomenon called general adaptation, for in that case the whole retina is stimulated by the same kind of light. It can apply to local adapta-

tion alone and even in local adaptation it cannot be considered a factor of primary importance. In 1838-1840 the loss of saturation experienced by a color on prolonged exposure to the eye was explained by Fechner⁴⁸ as due to the exhaustion or fatigue of the retinal elements. This explanation was adopted by Helmholtz, and became a feature of the Young-Helmholtz theory. Hering,⁴⁹ however, following a suggestion made by Godart, 1776,⁵⁰ and elaborated by Plateau, 1833-1835,⁵¹ chose rather to consider the retina compensating in function. A compensating retina, it is obvious, should not exhaust. Hering bore himself out in this general position by claiming that the eye is ordinarily exposed to stimulation by white light from 15-18 hours during the course of a day, and yet at the end of that time it has not noticeably lost in its sensitivity to white light.

Hering himself apparently has not based his claim on experimental evidence. At least he neither offers results of his own nor quotes from the work of others. His conclusion seems to be drawn wholly from general observation. He says (Ueber Ermüdung und Erholung des Sehorgans, *Arch. f. Ophthal.*, XXXVII., 1891, (3), p. 2): "Anderseits ist es eine bekannte Thatsache, dass wir des Abends nicht merklich schlechter sehen als des Morgens und dass dies auch dann noch der Fall ist, wenn dem Tage eine in hellen Räumen durchwachte Nacht und ein neuer schlafloser Morgen folgt. Also einerseits fortwährende Ermüdung und zwar eine so schnell—vor sich gehende, dass schon nach einer wenige Secunde währenden—Fixierung eines weissen Objects auf dunklem Grunde sich die Folgen der "Ermüdung" durch ein deutliches negatives Nachbild verrathen, und anderseits trotz solcher fortwährenden raschen Ermüdung keine merkliche Beeinträchtigung des Lebens selbst bei tagelanger Belichtung der Netzhaut." He contends (p. 1) that according to the theory of fatigue, advocated by Helmholtz and Fick, this should not be. During an exposure of several hours to white light, the eye never has a chance completely to recover, hence should become from beginning to end of the period progressively more fatigued.

This conclusion is not at all in agreement with experimental results obtained by C. F. Müller (*Versuche über den Verlauf der Netzhautermüdung*. Diss. inaug., Zürich. 1866), for example, who from the results of his tests of the loss of sensitivity of the eye to white light from morning to night, concludes: "Am Abende erscheint der Retina irgend ein Object nur in 0.49 derjenigen Helligkeit, in welcher es ihr am Morgen erschienen wäre." Moreover, he found that the shape of the curve of fatigue undergoes a very decided change during the course of the day. Aubert also disagrees with Hering. He says

⁴⁸ G. T. Fechner: *Pogg. Ann.*, XLIV., 1838, 221, 513; XLV., 1838, 227; L., 1840, 193, 427. The theory was conceived earlier by Scherffer (*Abhandlung von den zufälligen Farben*, Wein, 1765; also *Journal de Physique de Rozier*, XXVI., 175, 273), who explained the negative after-image by the conception that the retina is diminished in sensitivity by fatigue produced by previous stimulation.

⁴⁹ Ewald Hering: *Zur Theorie vom Lichtsinne*, 1874; *von Graefe's Archiv*, XXXVII., 1891, (3), 1, and 1892. XXXVIII., (2), 252.

⁵⁰ de Godart: *Journal de Physique de Rozier*, VIII., 1776, (1), 269.

⁵¹ Plateau: *Ann. de Chimie et de Physique*, LIII., 1833, 386; LVII., 1835, 337; *Pogg. Ann.*, XXXII., 1834, 543. More fully in *Essai d'une théorie générale*, etc. *Mem. de l'Acad. de Belgique*, VIII., 1834.

(Moleschott's Untersuchungen, VIII., 1862, 251; see also Beiträge zur Physiologie der Netzhaut. *Abhandlungen der Schlesischen Gesellschaft*, Breslau, 1861, 39): "Es erscheint mir also aus obiger Bemerkung hervorzugehen, dass im Laufe des Tages durch die Einwirkung des Lichtes die Empfindlichkeit unserer Retina fortwährend abnimmt, so dass wir am Abende weniger empfindlich gegen Licht sind, als des Morgens." Moreover, without supporting evidence either from general observation or from experiments on color, in fact in complete disregard of this evidence, Hering, as he has done in many other cases in his work on the optics of color, has generalized with regard to the retina's response both to white light and to colored light from the results of observations with white light alone. For example, it is scarcely necessary to point out that the eye cannot be exposed from 15-18 hours to colored light without loss of sensitivity to color. Without dwelling further, however, on the evidence for and against a compensation theory, it will be sufficient for our purpose here to point out that if one were to hold to a compensation theory in the Hering sense, it would be necessary for him to seek some other explanation than exhaustion for the loss of sensitivity of the eye, apparent or real, to color or brightness. Hering apparently conceives that this happens only in case two surfaces of different quality are juxtaposed, and then all that takes place is that each is induced over the other and the qualitative difference between the two tends to disappear. There is, then, no real loss of sensitivity of the eye to either. Both become alike because by induction they are mixed to equality. The following objections may be offered to the explanation. (1) As stated before, it cannot apply to general adaptation. Yet it is well known that the eye loses its sensitivity to color when the whole retina is stimulated by that color, in fact more rapidly than when only a part is stimulated, except perhaps in case of certain combinations of color and surrounding field. (2) It can apply to local adaptation only in case the two fields juxtaposed both belong to the brightness series. For example, when the eye is exposed for some length of time to a white surface contiguous to a black or a light gray to a dark gray, the lighter surface is observed to darken and the darker to lighten. This might be explained by the mixture of the two qualities by induction. The evidence afforded by the observation, however, is not at all differential, for the phenomenon may be explained just as well by exhaustion. A different situation entirely is presented, however, when the two contiguous surfaces are colored. In this case there is very little in the phenomenon that could by the most favourable interpretation be construed as a mixture to an intermediate color quality. For example, when red and blue are stared at in juxtaposition, we should expect, in terms of Hering's explanation, both surfaces to become purple with no more loss of saturation than would be attendant upon distributing each color uniformly upon both surfaces. This, however, is not at all what takes place. The prominent effect is loss of saturation. The two surfaces tend to become alike for the most part only because both tend towards gray. The blue, it is true, does acquire a tinge of violet, but it does this as the result of adaptation even when red is not juxtaposed. It probably does become slightly more reddish by being alongside the red, but the evidence of induction is not great. The red, likewise, may be modified a little by being alongside the blue, but the effect is even less noticeable than it is for the blue. Similar results are gotten with

green and yellow. In case the colors juxtaposed are complementary colors, the results of induction should be towards a cancellation to gray. But again the tendency towards gray which is actually observed affords no differential evidence for this theory of induction, because the shift towards gray can be explained just as easily in terms of the exhaustion theory. And that induction can have little to do with the phenomenon may be shown by the facts (1) that the tendency would have been towards gray had the whole retina been stimulated by one of the colors alone, and (2) that so far as can be told, the process is hastened little, if any, by the juxtaposition of the two colors. In the *Lichtsinne*, 1878, pp. 36-37 Hering describes the experiment upon which he bases his explanation of adaptation in terms of simultaneous induction. His device for stimulating the eye consists of a white and black surface juxtaposed. No attempt is made to extend the experiment to color. Moreover, in drawing his conclusions, no heed whatever is given to what would happen were the whole retina stimulated by light of one quality. This is a truly remarkable instance of a broad generalization made from a slender basis of fact.

The writer, then, does not wish it to be understood that he explains the fluctuation of minimal visual stimuli in terms of simultaneous induction. He has called this fluctuation a phenomenon of the adaptation and recovery of the sense organ, meaning by adaptation here, as in the original article, the progressive loss of sensitivity of the eye to colored and to colorless light caused by prolonged exposure. Just what the factors are in adaptation, will be made the subject of a further paper. They vary under different circumstances. In case of local adaptation, simultaneous induction is one of the factors, and in certain especial cases it may exert considerable influence, as is recognized in the test described above; but to make it the sole cause of the adaptation of the eye to its stimulus seems to the writer, in the face of the experimental evidence, to be little short of absurd.

In the earlier experiments it was found that by keeping the surrounding field constant and varying the stimulus, or conversely, by keeping the stimulus constant and varying the surrounding field, a difference in the period of fluctuation was obtained, showing itself chiefly in the phase of visibility. The same thing held in the recognized adaptation experiments. The variations in the phases of visibility and invisibility that were produced in the one, were produced in the other; the only departure from precise correspondence being that the differences were more marked in case of the recognized adaptation experiments, as would be expected from the longer duration of the process. The old series of Hering papers was used both in these experiments and in the experiments with stimuli of point area because combinations more favorable to rapid adaptation could be found in this series. Some of the combinations most favorable were the vermilion of the series on the blue-green, and the vermilion upon Hering gray No. 27; and some of the most unfavorable combinations were dark

red on yellow, and dark blue on yellow. The combinations favoring rapid adaptation gave in the fluctuation experiments a short phase of visibility and a long phase of invisibility, and conversely, the combinations unfavorable to rapid adaptation gave long phases of visibility and short phases of invisibility. Although the writer had carefully determined in an earlier experiment with large areas which were the favorable and which the unfavorable combinations, still in order to make the correspondence between fluctuation and adaptation still more complete, in cases of stimuli of very small area both adaptation and fluctuation experiments were conducted in the present study. As was the case in the earlier experiments, the advantages of a stationary stimulus and surrounding field had to be sacrificed in these experiments, because the use of the milk glass to reduce the saturation of the stimulus, as was done when a stationary system was used, would also have reduced the saturation of the color in the surrounding field. This would not have been desirable for the purpose of the experiment. Accordingly, the Masson disc with the broken radius of point breadth was substituted for the stationary system. In case of the adaptation experiments, a point of color of full intensity was pasted upon the various backgrounds and observed at the proper distance. In conducting this adaptation series with stimuli of point area, we were not only getting the results needed for comparison in our fluctuation series, but by using stimuli of full intensity, we were applying our test under precisely the same conditions used by Heinrich in his fluctuation experiments. In both cases the effect of the favorable and unfavorable combinations was plainly marked in the results. For the results of these experiments see Tables VII-X.

TABLE VII

OBS. R.—Showing that combinations that influence adaptation time correspondingly influence fluctuation for stimuli of point area just as they do for stimuli of larger area. Fluctuation series, stimulus-ring 0.3 mm. broad and of liminal intensity.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Blue.....	4.258	.81	1.930	.83	2.220	.450	6.215
Red....	Orange.....	6.041	.98	1.327	.59	4.552	.219	7.368
Red....	Yellow-green	6.10	.91	.933	.32	6.538	.152	7.033
Yellow..	Red.....	9.166	1.10	1.125	.26	8.147	.122	10.291

TABLE VIII

OBS. B.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red....	Blue.....	3.30	.82	2.871	.88	1.149	.870	6.171
Red....	Orange.....	5.083	.94	2.416	.75	2.103	.475	7.499
Red....	Yellow-green	4.125	.59	1.540	.64	32.678	.373	5.665
Yellow..	Red.....	6.230	.94	1.050	.32	5.933	.168	7.28

TABLE IX

OBS. R.—Showing that combinations that influence adaptation time correspondingly influence fluctuation for stimuli of point area just as they do for stimuli of larger area. Adaptation series, stimuli of point area and of full intensity.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red...	Blue.....	13.0	1.09	2.577	.76	5.044	.198	15.577
Red...	Orange.....	11.323	.90	1.112	.58	10.182	.098	12.435
Red...	Yellow-green	11.032	.87	.781	.32	14.122	.070	11.813
Yellow.	Red.....	200.	No	fluctu	ation.			

TABLE X

OBS. B.

Stimulus	Background	Vis.	M.V.	Invis.	M.V.	Vis. ÷ Invis.	Invis. ÷ Vis.	Period
Red...	Blue.....	5.761	.59	5.833	.654	.987	1.012	11.594
Red...	Orange.....	6.636	.98	4.723	.76	1.405	.711	11.359
Red...	Yellow-green	10.751	1.05	4.854	.97	2.215	.451	15.605
Yellow.	Red.....	200.	No	fluctu	ation.			

V. Conclusion

In conclusion the following points may be reviewed. (1) The work offered by Heinrich and Chwistek in support of the accommodation theory for the fluctuation of stimuli of point area was done with stimuli of full intensity. In using stimuli of this intensity Heinrich and Chwistek have created for themselves a special problem. The doctrine of fluctuation of attention has never been applied to the fluctuation of stimuli

strongly supraliminal in intensity. (2) Their strongest and most direct argument for the accommodation theory is their claim of having directly demonstrated a coincidence between involuntary changes of accommodation and fluctuation. The validity of this claim, however, rests primarily upon whether or not they have given a valid demonstration of the involuntary changes in accommodation. Their demonstration of involuntary changes in accommodation is strongly open to question. Employing 124 observers, the writer has been unable in a single case to make their popular demonstration work when care was taken to rule out extraneous factors which would themselves cause the phenomenon. And their technical demonstration with the ophthalmometer is in terms of a phenomenon which is described by de Schweinitz and others as one of the common phenomena of ophthalmometry due to eye-movement. The coincidence, then, which they claim to have observed between the fluctuation of stimuli of point area and changes in the curvature of the lens, is in all probability a coincidence between eye-movement and fluctuation. (3) Moreover, none of the evidence they have offered as indirectly proving the accommodation theory can be considered in any sense differential. All of it can be explained just as easily either in terms of the writer's adaptation theory or in terms of Loria's theory for the fluctuation of stimuli of point area. Some of it can even be explained in terms of any theory that has yet been advanced to account for the fluctuation of minimal visual stimuli. (4) The fluctuation of stimuli of point area presents no especial case. For (a) involuntary changes in accommodation are not an essential factor in these fluctuations. They take place for aphakial subjects apparently just as readily as for subjects with normal eyes. And (b) identified by the tests used by the writer in his earlier work these fluctuations correspond just as closely to adaptation phenomena as do the fluctuations of stimuli of larger area. (5) The fluctuation of minimal visual stimuli whether of large or small area is a phenomenon of the adaptation and recovery of the sense organ. And by adaptation is meant the progressive loss of sensitivity to colored and colorless light caused by prolonged exposure of the eye to these lights. It is not simultaneous induction. Simultaneous induction can be considered only as a minor factor in the adaptation of the eye to its stimulus.

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*THE PROBLEM OF LIGHTING IN ITS RE-
LATION TO THE EFFICIENCY OF
THE EYE¹*

UP to the present time the work on the problem of lighting has been confined almost entirely to the source of light. The goal of the lighting engineer has been to get the maximum output of light for a given expenditure of energy. Until recent years little attention has been given to the problem in its relation to the eye. It is the purpose of this paper to outline in a general way some of the more important features of this phase of the subject, and to give some of the results of work that is now being done on the problems that these features present.

Confronting the problem of the effect of lighting systems on the eye, it is obvious that the first step towards systematic work is to obtain some means of making a definite estimate of this effect. The prominent effects of bad lighting systems are loss of efficiency, temporary and progressive, and eye discomfort. Three classes of effect may, however, be investigated: (1) the effect on the general level or scale of efficiency for the fresh eye; (2) loss of efficiency as the result of a period of work; and (3) the tendency to produce discomfort. Of these three classes of effect the last two are obviously the more important, for the best lighting system is not the one that gives us the maximum acuity of vision for the momentary judgment or the highest

¹ This paper, with some changes, was read before the American Philosophical Society of Philadelphia, April 4, 1913.

level of efficiency for the fresh eye. It is rather the one that gives us the least loss of efficiency for a period of work, and the maximum of comfort.

In 1911 the American Medical Association appointed a committee to study the effect of different lighting systems on the eye. The writer was asked to share in the work of this committee. The problem presented to him was to furnish tests that would show the effect of different lighting systems on the eye, and more especially to devise, if possible, a test that would show loss of efficiency as a result of three or four hours of work under an unfavorable lighting system. In his work directed along these lines he has succeeded in getting methods of estimating effect which after eighteen months of trial seem sufficiently sensitive to differentiate between good and bad lighting systems with regard to these points. He has undertaken, therefore, to determine (1) the lighting conditions that give in general the highest level or scale of visual efficiency; (2) the conditions that give the least loss of efficiency for continued work; and (3) the conditions that cause the least discomfort. This plan of work, it is scarcely needful to remark, will involve a wide range of experimentation. The crux of the problem is, however, to secure reliable methods of estimating effect. Having these methods, the factors, whatever they may be, distribution, intensity, quality, position of the light relative to the eye, etc., can be varied one at a time and the effects be determined. From these effects it should not be difficult to ascertain what lighting conditions are best for the eye, and what is the relative importance of the factors that go to make up these conditions. Further, it should be possible on the practical side to test out and perfect a lighting system before it is put on the market; also to deter-

mine the best conditions of installation for a given lighting system; to investigate the effect of different kinds of type and paper on the eye; to study the effect of different kinds of desk lighting, etc. In short, it is obvious that the usefulness of such tests is limited along these lines only by their sensitivity.

A detailed description of the tests we are using has already appeared in print.² Time can not be given to them here. A brief report only of some of the results of the work in which they have been employed is possible in the time placed at my disposal.

In the study of the problems presented to us in this field it has been thought best to conduct the investigation at first along broad lines in order to determine in a general way the conditions that affect the efficiency and comfort of the eye. Later a more detailed examination will be made of the ways in which these conditions have been worked out in the various types of lighting systems in use at the present time. The following aspects of lighting sustain an important relation to the eye: the evenness of the illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity and quality. The first four of these aspects are very closely interrelated, and are apt to vary together in a concrete lighting situation, although not in a 1:1 ratio. For the purposes of this paper these aspects will be grouped together and referred to as the distribution of light and surface brightness in the field of vision, or still more generally as distribution. The ideal condition with regard to distribution is to have the field of vision uniformly illuminated with

² "Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort," *Transactions of the Illuminating Engineering Society*, 1913, VIII., pp. 40-60.

light well diffused and no extremes of surface brightness. When this condition is attained, the illumination of the retina will shade off more or less gradually from center to periphery, which gradation is necessary for accurate and comfortable fixation and accommodation.

The factors we have grouped under the heading distribution can be most conveniently discussed perhaps with reference to four types of lighting systems in common use to-day: illumination by daylight, direct lighting systems, indirect lighting systems and semi-direct systems. In the proper illumination of a room by daylight, we have been able thus far to get the best conditions of distribution. Before it reaches our windows or skylights daylight has been rendered widely diffuse by innumerable reflections; and the windows and skylights themselves, acting as sources, have a broad area and low intrinsic brilliancy, all of which features contribute towards giving the ideal condition of distribution stated above, namely, that the field of vision shall be uniformly illuminated with light well diffused and that there shall be no extremes of surface brightness. Of the systems of artificial lighting the best distribution effects, speaking in general terms, are given by the indirect systems. In this type of system the source is concealed from the eye and the light is thrown against the ceiling or some other diffusely reflecting surface, in such a way that it suffers one or more reflections before it reaches the eye. In some of the respects most important to the eye, this system gives the best approximation of the distribution effects characteristic of daylight of any that has yet been devised. The direct lighting systems are designed to send the light directly to the plane of work. There is in general in the use of these systems a tendency to concentrate the light on the work-

ing plane or object viewed rather than to diffuse it, and, therefore, a tendency to emphasize brightness extremes rather than to level them down. Too often, too, the eye is not properly shielded from the light source and frequently no attempt at all is made to do this. The semi-indirect systems are intended to represent a compromise between the direct and indirect systems. A part of the light is transmitted directly to the eye through the translucent reflector placed beneath the source of light, and a part is reflected to the ceiling. Thus, depending upon the density of the reflector, this type of system may vary between the totally direct and the totally indirect as extremes and share in the relative merits and demerits of each in proportion to its place in the scale. By giving better distribution this type of system is supposed also to be a concession to the welfare of the eye, but our tests show that the concession, at least for the type of reflector we have used,³ is not so great as it is supposed to be. In fact, installed at the intensity of illumination ordinarily used or at an intensity great enough for all kinds of work, little advantage is gained for the eye in this type of lighting with reflectors of low or medium densities; for with these intensities of light and densities of reflector, the brightness of the source has not been sufficiently reduced to give much relief to the suffering eye.⁴ Until this is done in home, office and

³ The reflectors we used were supplied to us by a prominent lighting corporation, interested neither in the manufacture nor the sale of lighting fixtures, in response to a request for a representative semi-indirect lighting system. Obviously, however, final conclusions should be reserved until the tests are extended to other types of reflectors.

⁴ The semi-indirect system used by us was but little better for the eye than the direct system. The direct system we employed was the one in general use throughout the building in which our tests were made. It was installed about six years

public lighting we can not hope to get rid of eye-strain with its complex train of physical and mental disturbances.

It is not our purpose, however, at this time to attempt a final rating of the merits of lighting systems. For that our work is still too young. Moreover, there are relatively good and bad systems of each type, and good and bad installations may be made of any system. What we hope to do is by making an appropriate selection and variation of condition and is, therefore, not of the most modern type. It seems to the writer safe to say, however, that it gives effects fully as good as most direct lighting in actual use in the country to-day. Furthermore, it is difficult to believe that any great injustice has been done to direct lighting, so far as this principle of lighting has been commercialized up to this time, by the selection of this system, because of the fact that very little less loss of efficiency was obtained from the semi-indirect lighting system, which on account of its similarity to indirect lighting represents, we have good reason to believe from our results, a greater modification of direct lighting for the welfare of the eye than any that is found within the class of direct systems. However, a final conclusion will be reserved until a more extensive investigation of the direct systems has been made. The writer further does not wish to be understood as contending that direct lighting can not be accomplished in a way that is not excessively damaging to the eye. Doubtless great improvement can be made in this type of lighting if proper attention is given to the fundamental principles governing the effect of light on the eye. It does not seem to the writer, however, that the principle of direct lighting offers as great possibilities in this direction as the indirect; still he permits this also to remain an open question in his mind. It is obvious that much can be accomplished for the welfare of the eye in cases both of the direct and semi-indirect systems by using sources of large area and of low intrinsic brilliancy, by removing them as much as possible from the field of vision, by employing better means of diffusing the light, etc.

tions to find out what the factors are that are of importance to the eye, and from this knowledge as a starting point to work towards reconstruction.

With regard to the effect of the distribution of light and surface lightness on the eye a brief statement will be given here only of its effect on efficiency; and in the consideration of efficiency loss of efficiency will receive the major part of our attention. No attempt will be made, for example, to present the results of the study of the factors producing discomfort. The study of these factors has constituted for us an entirely separate and independent piece of work investigated by separate and independent methods.

Our tests for loss of efficiency⁵ show that when the intensity and quality of the light

⁵ The tests were made in a room 30.5 feet long, 22.3 feet wide, and 9 feet high. The artificial lighting was accomplished by means of two rows of fixtures of four fixtures each. Each row was 6 feet from the side wall and the fixtures were 6 feet apart. The reflectors were in the different cases 19-26 inches from the ceiling. Clear tungsten lamps were used as source. The voltage was kept constant by means of a voltmeter and a finely graduated wall rheostat placed in series with the lighting circuit. In case of the direct system two bulbs making an angle of 180° were used for each fixture and the distribution was obtained by means of white slightly concaved porcelain reflectors 16 inches in diameter fastened directly above. In case of the indirect system corrugated mirror reflectors, enclosed in brass bowls, were used. For the semi-indirect system the distribution was obtained by means of inverted alba reflectors 11 inches in diameter which threw a part of the light against the ceiling and transmitted the rest directly to the room, minus a rather large absorption quantity. The daylight illumination came from three windows all on one side of the room and situated in a line parallel with the line of sight used when making the tests. These windows were so sheltered that it was never possible for them to receive light directly from the sun or from a brightly illuminated sky. Moreover, the

are equalized at the point of work, the eye loses practically nothing in efficiency as the result of three to four hours of work under daylight. It loses enormously for the same period of work under the system of direct lighting selected for our work and almost as much under the system of semi-indirect lighting. Under the system of indirect lighting, however, the eye loses but little more than it loses in daylight. The results of these tests show also that acuity of vision as determined by the momentary judgment is light from one of them, the one nearest the observer, was further diffused by passing through a diffusion sash made of double thick glass ground on one side. The intensity in foot-candles was made equal at the point of work for all the systems employed. In making this equalization the light was photometered in five directions at the point of work: with the receiving surface of the photometer in the horizontal plane, at angles of 45° and 90° pointing towards the observer, and at angles of 45° and 90° pointing in the opposite direction. In installing the lights in the different systems it was impossible to make the intensity equal in all of these directions. Care was taken to make it equal in the plane of the test card, *i. e.*, the vertical plane, and as nearly as possible equal in the other planes. The Sharpe-Millar portable photometer was used to make these measurements, also another method mentioned in a former paper (*op. cit.*, p. 49) which is more sensitive to daylight illumination than is the Sharpe-Millar method. The effect of varying distribution of light was thus tested under conditions in which quality and intensity were reduced as nearly to a constant as was possible with the systems employed. The intensity in the vertical plane was made in each case 1.4 foot-candles or approximately so. Space can not be taken here for an engineering specification of the installations used and the lighting effects produced. A full report of the work including detailed brightness and illumination measurements, photographs showing the illumination effects obtained, descriptions of installations, etc., will be published in the *Transactions of the Illuminating Engineering Society*.

higher for the same foot-candles of illumination for the daylight system than for the systems of artificial lighting, and that for the latter systems, it is highest for the indirect system, next highest for the semi-indirect system, and lowest for the direct. It will thus be seen that for all purposes of clear seeing, whether the criterion be maximum acuity or the ability of the eye to hold its efficiency for a period of work, the best results are given in order by the systems that give the best distribution of light and surface brightness. The effect of distribution is not so great, however, on the ability of the fresh eye to see clearly as it is on its power to hold its efficiency.

The loss of efficiency found in the above work seems to be predominantly, if not entirely muscular, for the tests for the sensitivity of the retina show practically no loss of sensitivity as the result of work under any of the lighting systems employed. The following reasons are suggested why the muscles of the eye giving both fixation and accommodation should have been subjected to a greater strain by the systems of direct or semi-direct lighting, than by the system of indirect lighting or daylight. (1) The bright images of the sources falling on the peripheral retina which is in a perpetual state of darkness-adaptation, as compared with the central retina, and is, therefore, extremely sensitive in its reaction to such intensive stimuli, set up a reflex tendency for the eye to fixate them instead of, for example, the letters which the observer is required to read. (2) Likewise, a strong reflex tendency to accommodate for these brilliant sources of light, all at different distances from each other and the lettered page, is set up. (3) These brilliant images falling on a part of the retina that is not adapted to them, causing as they do acute discomfort in a very short period of time, doubtless induce spasmodic contractions of the muscles which both disturb the clearness of

vision and greatly accentuate the fatiguing of the muscles. The net result of all these causes is excessive strain, which shows itself in a loss of power to do work. In the illumination of a room by daylight, however, with a proper distribution of windows, the situation is quite different. The field of vision contains no bright sources of light to disturb fixation and accommodation and to cause spasmodic muscular disturbances due to the action of the intensive light sources on the dark-adapted and sensitive peripheral retina. As has already been pointed out, the light waves have suffered innumerable reflections and the light has become diffuse. The field of vision is comparatively speaking uniformly illuminated and there are no extremes of surface brightness. The illumination of the retina, therefore, falls off more or less gradually from center to periphery, as it should to permit of fixation and accommodation for a given object with a minimum amount of strain.

It is not our purpose, however, to contend that distribution is the only factor of importance in the illumination of a room. We have chosen to begin our work with types based on distribution, only because it has seemed to us, both from our own work and from a survey of the work done by others, that this is the most important factor with which we have yet to deal in our search for the conditions that give minimum loss of efficiency and maximum comfort in seeing. The quality of light and its intensity at the source are already pretty well taken care of, apparently better taken care of, at least in general practise relative to their importance to the eye, than is distribution. A systematic study of factors, however, can not stop with an investigation of the effect of distribution alone. The intensity and quality of light must also be taken into account. For example, one of the most persistent questions asked by the illuminating engineer is, "How much light should be used with a given

lighting system to give the best results for seeing?" We have undertaken, therefore, to determine the most favorable range of intensity for the four types of distribution mentioned above. Curves have been obtained showing the effect on the efficiency of the eye of three or four hours of work under different intensities of light, for the direct and semi-indirect systems; and rough comparisons have been made for the indirect system and for daylight. Detailed tests will be made for these latter two systems early next year. Our tests show, in general, the following results. A very wide range of intensity is permissible for daylight and the indirect system. For the semi-indirect system the eye falls off heavily in efficiency for all intensities with the exception of a narrow range on either side of 2.2 foot-candles, measured at the level of the eye at the point of work with the receiving surface of the photometer in the horizontal plane. For the direct system no intensity can be found for which the eye does not lose a very great deal in efficiency as the result of work. Thus it seems that distribution is fundamental. That is, if the light is well distributed and there are no extremes of surface brightness as is the case for daylight and the indirect systems of artificial lighting, the ability of the eye to hold its efficiency is, within limits, independent of intensity. In short, the retina is itself highly accommodative or adaptive to intensity, and if the proper distribution effects are obtained, the conditions are not present which cause strain and consequent loss of efficiency in the adjustment of the eye.

Details of the conditions of installation and of the methods of working can not be given here. It will be sufficient to state that the work was done in the same room, with the same fixtures, and in general with the same conditions of installation and methods of working as were used in the tests for distri-

bution. Nor can a full statement of results be made. Time will be taken, however, for a more detailed examination of the results obtained for the direct and semi-indirect systems. For the semi-indirect systems, our test showed that the intensity most favorable to the eye was secured when the photometric reading with the receiving surface in the horizontal plane showed 2.2 foot-candles of light at the point of work, 1.52 foot-candles in the 45° position, and .58 foot-candle in the vertical position. At this intensity of illumination, the semi-indirect system, so far as its effect on the eye's loss of efficiency is concerned, compares fairly well with the indirect system at such ranges of intensity as we have employed. At intensities appreciably higher than this most favorable value, or lower, the loss of efficiency is very great. At the intensity commonly recommended in lighting practise, the semi-indirect system is almost, if not quite, as damaging to the eye as the direct system. The intensity recommended by the Illuminating Engineering Society, for example, in its primer issued in 1912, ranges from 2-3 to 7-10 foot-candles, depending upon the kind of work. Five foot-candles is taken as a medium value. This medium value, it will be noted, is more than double the amount we have found to give the least loss of efficiency for the type and installation of semi-indirect system we have used. The intensity we have found to give the least loss of efficiency for this type of lighting, does not, however, give a maximum acuity of vision as determined by the momentary judgment. At an intensity that does give maximal acuity for the momentary judgment the eye runs down rapidly in efficiency. That is, in this type of lighting, one or the other of these features must be sacrificed. High acuity and little loss of efficiency can not be had at the same intensity. They could both be had only under the indirect system and daylight. How-

ever, the amount of light we find to give the least loss of efficiency seems to be sufficient for much of the work ordinarily done in the home or office. It is not enough, though, for drafting or work requiring great clearness of detail.

In case of the direct system, we were able to improve the conditions, so far as loss of efficiency is concerned, by reducing the intensity; but the system never proved so favorable in this regard as even the semi-indirect system. In the tests made under the direct system care was taken to have the fixtures in the same position in the room in every case as they were for the semi-indirect system. The most favorable intensity is secured by an installation that gave 1.16 foot-candles in the horizontal, .85 in the 45° position and .45 in the vertical. At this intensity, however, the loss in the efficiency of the eye for three hours of work was almost four and one half times as great as for a wide range of intensities for either the indirect system or daylight.

Two facts, then, may be emphasized at this point. (1) Of the lighting factors that influence the welfare of the eye, those we have grouped under the heading distribution apparently are fundamental. They seem to be the most important we have yet to deal with in our search for the conditions that give us the minimum loss of efficiency and the maximum comfort in seeing. If, for example, the light is well distributed in the field of vision and there are no extremes of surface brightness, our tests seem to indicate that the eye, so far as the problem of lighting is concerned, is when the proper distribution is present, intensities high enough to give the maximum discrimination of detail may be employed without causing appreciable damage or discomfort to the eye. (2) For the kind of distribution effects given by the majority of lighting systems in use at the present time, our results

show that too much light is being employed for the welfare and comfort of the eye.

The effect of quality of light on the eye has been the subject of much discussion and much misunderstanding. There seems to be a feeling even among lighting engineers and ophthalmologists that colored light gives better results for seeing than white light. Some, for example, hold that the kerosene flame furnishes the ideal source of light and that its virtues are due largely to the yellow quality of the light it gives off. While the writer has not as yet begun a systematic study of the effect of quality of light, and while he is, therefore, not as yet willing to commit himself on this point, he will say that when intensity and distribution are equalized, an installation of clear carbon lamps, which gives a light comparatively rich in yellow and red, causes the eye to fall off more in efficiency as the result of 3-4 hours of work than an installation of clear tungsten lamps, the light from which is more nearly white. In short, the question whether or not white or colored light is better for the eye can not be answered until definite tests are made of this point alone under conditions in which all other factors are rendered constant. The effects of the kerosene flame, for example, as compared with other sources of illumination, must be tested under a system of installation that gives the same intensity at the source, and, as nearly as possible, the same distribution in the field of vision as is given by other illuminants. This has not been done at all. Our judgment of the comparative merits of the color quality of the light given by it have been based on the roughest kinds of impression, obtained under conditions of installation in which there has been no attempt at control of the other factors that influence the effect of light on the eye. The work that has been done up to this time on the relation of quality of light to seeing has been confined to visual acuity as determined by the

momentary judgment, and even this work which alone can give no safe grounds at all for drawing general conclusions as to the effect of light on the welfare of the eye, shows, whenever the comparison has been made, that white light gives a greater acuity of seeing than light with a dominant color tone. If, as has been maintained by some on the grounds of their working experience, the kerosene flame is easier on the eye than the more modern sources of illumination, the writer would be inclined, more especially in view of his results on the effect of differences in intensity on the efficiency of the eye, to ascribe the benefit, whatever there may be, to the low intrinsic brilliancy of the kerosene flame. For, as has already been stated, it may be safely said that for the kind of distribution effects we are getting from the large majority of our lighting systems, too much light is being used for the welfare and comfort of the eye. Added to this is the effect of the position of the light in the field of vision. The kerosene lamp may be placed at the back or side of the person using it, and, if in the field of vision, it is usually at or near the level of the eye. In the two former cases the effect of concealed lighting is given, and in the latter case the lamp occupies the most favorable position possible for an exposed source. That is, if the source of light is to be in the field of vision at all, it should be as nearly as possible at the level of the eye. This is because of the greater tendency of a light source to produce discomfort and loss of efficiency when its image falls on the upper and lower halves of the retina than when it falls in the horizontal meridian. These facts have been clearly brought out in our work on the effect of position of the light in the field of vision.

In addition to studying the conditions that give us maximum efficiency, it is important to determine the lighting conditions and eye factors that cause discomfort. In fact, it

might well be said that our problem in lighting at present is not so much how to see better as it is how to see with more comfort and with less damage to the general health on account of eye-strain. Any comparative study of the conditions producing discomfort necessitates a method of estimating discomfort. As stated earlier in the paper, our method of estimating discomfort is entirely distinct and separate from our method of studying efficiency. Time can not be taken here to go into details of either the method or of the results of this study. It will be sufficient to say that the effect of distribution of light and surface brightness, intensity, and quality are also being studied in their relation in the comfort as well as to the efficiency of the eye.

In conclusion, the writer wishes to point out that no one of the factors he has mentioned can be safely omitted in the search for the most favorable conditions of lighting. Nor can one be investigated and a correlation between it and the others be taken for granted. We have been content, heretofore, to base our conclusions with regard to the relation of a lighting system to seeing on the conventional visual acuity test. While this test may tell us something about the general level or scale of efficiency of the fresh eye, it can tell us nothing of loss of efficiency, because the muscles of the eye, although they may have fallen off enormously in efficiency, can under the spur of the will be whipped up to their normal power long enough to make the judgment required by the test. Moreover, it tells us nothing of the conditions that produce discomfort. In short, the general level or scale of efficiency of the fresh eye, loss of efficiency as the result of work, and the tendency to produce discomfort constitute three separably determinable moments, no one of which should be neglected in installing a lighting system.

C. E. FERREE

A PRELIMINARY STUDY OF THE DEFICIENCIES OF
THE METHOD OF FLICKER FOR THE
PHOTOMETRY OF LIGHTS OF
DIFFERENT COLOR

A PRELIMINARY STUDY OF THE DEFICIENCIES OF THE METHOD OF FLICKER FOR THE PHOTOMETRY OF LIGHTS OF DIFFERENT COLOR¹

BY C. E. FERREE AND GERTRUDE RAND

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SYNOPSIS

A satisfactory method of photometry should combine the following features. (1) It should enable one to detect small differences in luminosity and to reproduce results for a given observer with a small mean variation and for a number of observers with a comparatively small mean variation. That is, the method should possess an adequate degree of sensitivity. (2) It should be known either to possess of itself logical sureness of principle or its results must agree in the average with those of some method which can be shown to have this sureness of principle. The method of flicker probably satisfies the first of these requirements better than the equality of brightness method. It does not, however, possess of itself the needed sureness of principle, nor have its results been shown to agree in the average with any method which is accorded sureness of principle. Points are enumerated in the paper appended which raise doubt with regard to the correctness of the photometric balance obtained by the method of flicker. Only one of these is discussed, namely, the influence of the time element in the exposure of the eye to the lights to be compared. With regard to this point, it is shown from experimental data (1) that the sensations aroused by lights differing in color value rise to their maximum brightness at different rates; and (2) that the single exposures used in the method of flicker are much shorter than is required for these sensations to rise to their full value. The eye, therefore, is very much underexposed to its stimulus by the method of flicker. That is, the rate of succession used in the method of flicker is too fast for the single impressions to arouse their maximum effect in sensation and too slow for the successive impressions to add or summate as much as they would need to do to rise to their full value or perhaps even to a higher value than would be given by the individual exposures. Only one other possibility for a correct balance remains,—equality is attained at some value lower than the full value. This can not be assumed, however, without violating well-known laws relating to the factors which influence persistence of vision.

The principal point of discussion, then, is to what degree it should be held that the difference in lag between the sensations aroused by the single exposures used in the method of flicker is obliterated in a succession of exposures. Broadly considered, three positions are possible with regard to the point for the rates of succession that are employed in the method of flicker. (1) The difference is not obliterated at all. In this case the photometric balance should deviate from the true balance in direct pro-

¹ Paper read by C. E. Ferree at the Philadelphia section of the Illuminating Engineering Society, January 16, 1914.

portion to the difference in lag for the single exposures. (2) The difference is in part obliterated, but it is still present to a degree which renders the method untenable for precise work. And (3) the difference is entirely obliterated or so nearly so as to be of no practical consequence to the validity of the method. The second is approximately the position taken in this paper. The following evidence is offered in support of this position. (a) At high intensities of light the writers get by the method of flicker a deviation from the true photometric balance, as determined by the equality of brightness method, in a direction which corresponds to the difference in lag between these colors at high intensities as determined both in their own laboratory¹ and by Broca and Sulzer. (b) At low intensities they get a difference in lag for the colors which is in the same direction as the deviation obtained by Ives and Luckiesh at low intensities (the reverse Purkinje effect). (c) A change in the relative lengths of exposure to the two lights in the method of flicker produces a deviation from the equality of brightness balance which again corresponds in direction to the changes that are produced in the sensations aroused by the single exposures when similar changes are made in the relative lengths of exposure. And (d) determinations made at several intensities of light by the method of flicker show a deviation from the equality of brightness balance which is many times the smallest difference in brightness that can be detected by the method. Moreover, in their own results the writers find that these deviations in every case correspond to the difference in lag given by lights of the same order of magnitude of intensity, so far as can be judged from the determinations of lag that have been made up to this time. When, however, determinations have been made on a larger number of observers, individual differences may be found in the amount and distribution of lag just as they have been found in the amount and direction of the deviation of the flicker from the equality of brightness balance. Later in the interests of a fairer comparison the writers hope to make in every case compared the determination of lag and the photometric determinations on the same observer.

The writers have preferred to call the work of which this paper is a brief report a preliminary study for the following reasons. (1) Only one of the points directly pertaining to the method of flicker that should be investigated has been taken account of in the work. And (2) to complete the chain of evidence needed for this point, a more especially directed and perhaps more careful determination should be made than has yet been done of the time required for visual sensations colored and colorless to rise to their maximum of intensity. Such a study with especial reference to the needs of photometry is now in progress in our laboratory, but is as yet unfinished.²

¹ See this paper, footnote 1, pp. 125-130.

² In the work now in progress in our laboratory, attention will be paid to the following points. In case of colors, care will be taken to use lights of a small range of wave-length. The intensities of the lights used will be specified photometrically and radiometrically. The white light will in addition be specified either spectro-photometrically or spectro-radiometrically. For the sake of the comparisons needed in

A satisfactory method of photometry should combine the following features. (1) It should enable us to detect small differences in luminosity and to reproduce our results for a given observer with a small mean variation and for a number of observers with a comparatively small mean variation. That is, the method should possess an adequate degree of sensitivity. (2) It should be known either to possess of itself logical sureness of principle, or its results must in the average agree with those of some method which can be shown to possess this sureness of principle. Methods having these features have been developed for the photometry of colorless light. The problem of the photometry of colored light, however, has presented great difficulty.

METHODS OF PHOTOMETERING COLORED LIGHT.

The methods for photometering colored light may be grouped under two headings: the direct methods and the indirect methods. In the former class we have the method of direct comparison or, as it is sometimes called, the equality of brightness method. Of the latter class the method of flicker has received the greatest amount of attention and has been the most favored. It will be the purpose of this paper (1) briefly to compare the relative advantages and disadvantages of the method of flicker and the equality of brightness method with regard to sensitivity; (2) to show that the method of flicker, so far as it has been developed up to the present time, does not seem to possess of itself the sureness of principle needed to meet the requirements of a satisfactory method; and (3) to show that as yet its results have not been found satisfactorily to agree in the average with those of any method which can be shown to have this sureness of principle. In a

the photometric work, all determinations for lights differing in composition will be made at the different intensities employed with stimuli equalized photometrically. Comparative results will be obtained for the same observers for the best of the methods already in use, and three new methods will be introduced. In part, results will be obtained for observers who have also been employed in the work on the method of flicker. The work will be done for different intensities of light, and both under dark and light room conditions. In a survey of the work done up to the present time, one can not help but note that too little care has been taken to observe even some of the most essential of the above conditions.

later paper a new method of photometry will be described which possesses approximately as high a degree of sensitivity for color work as the method of flicker and gives results which agree much more closely in the average with those obtained by the equality of brightness method. The second of the above points will be shown as follows. It will be pointed out that at the rate of speed at which the impressions are given in the method of flicker, the eye is very much underexposed to its stimulus. It can reasonably be assumed that this underexposure causes a reduction of the intensity of the sensation, and should lead, therefore, to a false estimation of the brightness of the colors. In fact, at the rate of rotation of the exposure apparatus required for lights of the order of intensity employed in practical work, this reduction produces for the observers we have used an effect similar to the Purkinje phenomenon.¹ At least a deviation from the equality of brightness values is found in our results for such intensities which accords well with the Purkinje phenomenon. That is, reds and yellows are underestimated in brightness, and blues and greens are overestimated. And (b) it will be shown that flicker itself, the phenomenon on which the equalization at the photometric screen is based, is subject to variations depending upon a number of factors the effect of which has not in all cases been adequately studied and in some cases not even recognized. An investigation of one of these alone, the effect of varying

¹ We do not mean to draw too close an analogy here between the effect on the brightness of sensation produced by keeping the intensity of light constant and reducing the time of exposure of the eye to the light, and the effect produced by keeping the time of exposure of the eye constant and reducing the intensity of the light employed (the Purkinje phenomenon). In attempting to interpret the effect produced by the short exposures used in the method of flicker, our data should be taken primarily from the results showing the relative rise of sensation to its maximum for white light and lights of the different colors. (See discussion of the development time of sensation, pp. 118-130). It is quite possible and in fact quite probable from Broca and Sulzer's results, for example, that for a part of the upward course blue and green rise faster than red, and conversely for a part of the course red rises faster than blue and green. (Yellow was not used by Broca and Sulzer.) The results of Broca and Sulzer are cited on this point, not by any means because their method of making the determination is the freest from criticism of any that have yet been used, but because they alone have attempted to plot the comparative curves for the different colors and white light at different points from the threshold to the maximum.

the ratio of the time of exposure of the eye to the lights to be compared, is enough to lead one seriously to question whether the method of flicker can be safely used in the work of heterochromatic photometry, at least not without calibration, and perhaps not without an amount of calibration which is in itself prohibitive of the use of the method in practical work. The third point will be covered in the following way. (1) It will be pointed out that the only method that has thus far been used as a standard with which to compare the method of flicker has been the equality of brightness method. The selection of this method as a standard has been recommended among others by Whitman, Wilde, and Schenck, and a comparison of the results of the two methods, more or less complete, has been made by a number of experimenters. And (2) it will be shown both from our own work and from a very great preponderance of the work done by others who have made the comparison, that the results by the method of flicker do not agree in the average with those obtained by the equality of brightness method; and, therefore, that justification for the adoption of the method of flicker can not yet, at least, be fairly claimed through its agreement in result with the equality of brightness method.

The Equality of Brightness Method.—With regard to sensitivity in the photometry of lights of different color, the equality of brightness method has the following disadvantages. (1) Small differences in luminosity can not be detected because the actual difference present is masked by the difference in color quality. (2) Results for a given observer can not be reproduced within a small limit of variation, because the ability to do this in turn presupposes the ability to detect small differences which, as has just been stated, can not be done. (3) Results can not be reproduced from observer to observer within a small limit of variation because (a) the sensitivity to color varies more among observers than does, for example, the sensitivity to brightness, hence there is a variable amount of the disturbing factor of color present for different observers; and (b) because the standard or pattern for the judgment of equality differs

more from individual to individual when the factor of color is present than when it is not. That is, in any photometric judgment the observer must decide for himself what he will call equality and make all his judgments conform to this pattern or standard. When color is present to interfere with the judgment of equality, the selection of this standard varies more for different observers than it does when no color is present. With regard to all the points on which sensitivity depends, therefore, the equality of brightness method may be said to possess a low degree of sensitivity.

The Method of Flicker.—The method of flicker possesses greater sensitivity than the equality of brightness method. That is, smaller differences in the luminosity of the photometric surfaces can be detected, and the judgment of equality is surer and more reproducible.¹ This is because the disturbing factor of color difference in the impressions to be compared is eliminated from the judgment. That is, instead of being given simultaneously, the stimuli are given in succession and at such a rate that all color differences between them disappear, and the brightness impressions are permitted to develop in sensation unobscured by differences in color quality.

The use of the phenomenon of flicker to detect a difference in brightness between two illuminated surfaces can best be understood possibly by considering the phenomena that take place when successive impressions of colored and colorless light are made upon the retina at different rates of speed. When the retina is exposed successively to colorless lights differing in brightness, the following phenomena take place. When the rate of succession is low, the impressions remain

¹ This higher degree of reproducibility can be claimed perhaps only for the judgments given by a single observer. It does not seem to obtain to any considerable extent, so far as results are available for comparison, when results are compared from observer to observer. For example, in a group of eighteen observers Ives gets differences as great as 159 per cent. for .481 μ , 114 per cent. for .498 μ , 26 per cent. for .518 μ , 18 per cent. for .537 μ , 13 per cent. for .556 μ , 10 per cent. for .576 μ , 28 per cent. for .595 μ , 65 per cent. for .615 μ , 86 per cent. for .635 μ , and 122 per cent. for .655 μ . The percentage of average variation from the mean for these observers is 17 per cent for .481 μ ; 13.4 per cent. for .498 μ ; 6 per cent. for .518 μ ; 3 per cent. for .537 μ ; 2.75 per cent. for .556 μ ; 2.2 per cent. for .576 μ ; 5.4 per cent. for .595 μ ; 9.5 per cent. for .615 μ ; 13.2 per cent. for .635 μ ; and 19.3 per cent. for .655 μ . (*Philos. Mag.*, 1912, 24, Ser. 6, pp. 853-863.)

more or less separate and distinct. At rates higher than this, we have in order Fechner's colors,¹ flicker, and the fusion of the two impressions into a uniform gray. When the eye is exposed successively to colored and colorless light, the following phenomena take place. At low rates, we have again the more or less separate successions of the two impressions. At rates slightly higher than this, we have first a phenomenon that may be called by analogy color flicker, and then an intermingling of color and brightness flicker. At still higher rates we have color fusion, brightness flicker, and complete color and brightness fusion. Thus, both in case of colored and colorless light, brightness flicker seems to be a phenomenon due solely to the succession at certain rates of speed of impressions differing in luminosity or brightness. Moreover, the phenomenon is very sensitive to changes in the luminosity of the successive impressions. That is, a very slight change in one of the impressions will produce flicker when there is no flicker, or will cause a noticeable change in its amount when there is flicker. Flicker thus becomes a very sensitive means of detecting brightness difference. This sensitivity, however, is not so great in case of colored as it is in case of colorless light. It would in fact in all probability be very low were it not for the fortunate fact that color fusion takes place at a very much lower rate of succession than brightness fusion.

Concerning the ease and sureness of making the judgment, then, the case with regard to the method of flicker may be summed up as follows: By giving the impressions to be compared to the retina successively at a certain rate of speed, the disturbing element of color difference, which so interferes with the detection of brightness difference when the impressions are given simultaneously, is eliminated, and the phenomenon of brightness flicker stands out clearly in a field uniform as to color quality. That is, by using a method of successive impressions we have succeeded in eliminating the

¹ Fechner's colors are best observed when the successions are made by rotating discs made up of white and black sectors, or by discs specially constructed for the purpose. This phenomenon occurs at a rate of speed near the upper limit required to give separate impressions, and consists of impressions of color mingled with the more or less separate impressions given by the white and black sectors.

feature that renders the comparison of the brightness of the simultaneous impressions so difficult to make, namely, the difference in color quality between the impressions to be compared. The judgment, then, is easy, and the principle on which the equalization is based seems to be clear. The method has come to have many supporters, but other things besides the sureness of judgment must be taken into account. This brings us to a consideration of our second point, namely, the method of flicker when applied to the photometry of lights of different color does not seem to possess the sureness of principle needed to meet the requirements of a satisfactory method. We have two reasons for making this assertion. In the first place, as we have already stated, at the rate of speed at which the impressions are given in the method of flicker, the eye is very much underexposed to its stimulus. And in the second place, flicker, the phenomenon on which the equalization is based at the photometric surface, is subject to many variations depending upon a number of factors the bearing of which on the application of the phenomenon to photometry, has not in all cases been adequately studied, and in some cases not even recognized. A few of these may be suggested in passing. (1) The intensity of illumination and the influence it exerts on the speed of alternation that has to be used in order to give the method maximum sensitivity. (2) The different rates of speed required for the fusion of the different colors, and the varying lower limit this difference puts upon the rates of speed that can be used. (3) The effect of the saturation of the colors used on the fusion rate. (4) The effect of field size. (5) The effect of the ratio of the time of exposure of the eye to the lights to be compared; etc. A better knowledge than we now have of the effect of these factors is, the writers believe, of fundamental importance in the employment of the phenomenon of flicker in the photometry of lights of different colors. At a later date they hope to report the results of a systematic study of these factors. In the present paper, the effect of only one of them will be considered, namely, the ratio of the time of exposure of the eye to the lights to be compared. An investigation of this

point alone is enough to lead one seriously to question whether the method of flicker can safely be used in the work of heterochromatic photometry, at least not without calibration, and perhaps not without an amount of calibration which is in itself prohibitive of the use of the method in practical work.

THE ACTION OF LIGHT ON THE EYE UNDER THE CONDITIONS IMPOSED BY THE METHOD OF FLICKER.

Both of the above points will probably be more easily understood if a brief consideration is given to the way the eye responds to colored and colorless lights when the impressions are given to it in the manner they are given in the method of flicker. The eye is not an ideal sense organ, that is, it does not respond at once with its full intensity of sensation at the beginning of stimulation, nor does the sensation cease with the cessation of stimulation. It takes, for example, an interval of time for the sensation proper to a given stimulus to rise to its maximum; and also an interval to die away after the stimulation has ceased, depending for its length upon several factors.¹

The interval of time required for a sensation to rise to its maximum will be called in this paper the development time of sensation. Plateau in 1834² first expressed the belief that

¹ There are two phases to this after-effect, positive and negative. The positive alone concerns us here. In this phase, which is often called the persistence of vision, the original sensation tends to persist in its original color and brightness. More accurately described, however, it rapidly loses in color and rapidly darkens. In the negative phase there is a brightness reversal, that is, what is light in the original sensation becomes dark, and the color changes to the complementary color. The negative phase is much longer than the positive. The length of the positive depends upon many factors: the intensity of the stimulus, the time of exposure of the eye to the stimulus, the state of adaptation of the eye, the general illumination of the field of vision, the brightness of the local pre-exposure and post-exposure, etc. Unless the eye is put under very especial conditions of stimulation, the duration of the positive phase is very short indeed, in fact, momentary. For a further discussion of this point with reference to the method of flicker, see appendix.

² As early as the time of Bacon it was noted that there is a period of inertia in vision. ("At in visu (cujus actio est perniciosissima) liquet etiam requiri ad eum actuandum momenta certa temporis: idque probatur ex iis, quae propter motus velocitatem non cernuntur; ut ex latione pilae ex sclopeto. Velocior enim est praeter-volatio pilae, quam impressio speciei ejus quae deferri poterat ad visum.")—"Novum Organum," lib. II., Aph. XLVI.). Later Beudant (*Essai d'un Cours Elementaire*

color sensation does not come at once to its maximum. He, and later Fick¹ in 1863, showed that when a sector of white paper passes very rapidly only once before the eye it looks to be a dark gray. With the experiments of Exner in 1868, the work of determining the development time of visual sensation was definitely begun. Different methods of making the determination have been used by different investigators, and different results have been obtained. There is, however, among the different results a certain amount of agreement. At least the order of magnitude of the development time can be fixed within certain limits. The chief points of interest in these investigations have been (1) to compare the development time of the different sensations of color with each other and with that of colorless sensation; and (2) to determine whether the intensity of the stimulus has any effect upon the development time. All who have made the comparison have found that each of the color sensations has a development time different from the colorless sensations; all with the exception of Dürr and Berliner, that each of the colors has a different development time; and all with the exception of Dürr, that an increase of intensity shortens to some extent the development time of all sensations.

A table (Table I.) has been prepared showing the development time obtained by each of these men for the different et General des Sciences Physique: Partie Physique,' p. 489, 3me edition) also stated that an object which moves with extreme rapidity before the eye is not perceived because impressions are not made on the eye instantly. Plateau ('Nouveaux Memoirs de l'Academie Royale des Sciences et Belles Lettres de Bruxelles,' 1834, 8, p. 53) made the observation that when a bit of white paper passes very rapidly before the eye, it appears not white but gray. He was the first to express the belief that color sensation also does not come at once to its maximum of intensity. Swan (*Trans. Roy. Soc. Edinb.*, 1849, 16, pp. 581-603) observed that the "light of the sky seen immediately over a ball in its descent through the air, seemed less bright than at those parts of the retina where the action of light had not been interrupted by the passage of the dark body"; and conducted some experiments to determine the intensity of light sensation with short exposures. Exposing the eye to lights of different intensities for intervals ranging from $1/100$ to $1/16$ of a second, colorless 'lights of different intensity produce like portions of their total effect on the eye in equal times.' While he does not directly determine the interval required for the light sensation to come to its maximum, he estimates it from the results of his experiments with short exposures to be about $1/10$ of a second.

¹ Fick, A. *Archiv für Anatomie und Physiologie*, 1863, p. 739.

TABLE I

SHOWING A COMPARISON OF THE DEVELOPMENT TIME OF VISUAL SENSATION WITH THE AVERAGE TIME OF EXPOSURE OF THE EYE TO ITS STIMULUS USED IN OUR EXPERIMENTS WITH THE METHOD OF FLICKER.

		Sensation	Development Time	Average Time of Exposure of Color by Method of Flicker
Exner ¹	1868	White	5 intensities: .118-2.87 sec.	.0178 sec., when the value of the colored sector was 180°.
Kunkel ²	1874	Different colors	.057-.133	
Charpentier ³	1887	White,	5 intensities .014-.049	
Lough ⁴	1896	White,	5 intensities .090-.148	
Dürr ⁵	1902	White,	2 intensities: .266	.0213 sec., when the value of the colored sector ranged from 45°-315°.
Martius ⁶	1902	Different colors	.541	
		White	6 intensities: .013-.093	
Broca and Sulzer ⁷	1903	Different colors	.020-.090	
		White	8 intensities: .031-.125	
McDougall ⁸	1904	Different colors	.07 -.125	
		White	12 intensities: .049-.2	
Büchner ⁹	1906	Different colors	.100-.108	
		White	3 intensities: .033-.230	
Berliner ¹⁰	1907	Different colors	.130	

¹ Exner, S., 'Ueber die zu einer Gesichtswahrnehmung nöthige Zeit.,' *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften, Math.-Phys. Classe*, 1868, 58, pp. 601-632.

² Kunkel, A., 'Ueber die Abhängigkeit der Farbenempfindung von der Zeit,' *Pflüger's Archiv*, 1874, 9, p. 197.

³ Charpentier, 'Sur la periode d'addition des impressions illuminismes,' *Comptes Rendus Société de Biologie*, 1887, 4, pp. 192-194.

⁴ Lough, 'The Relations of Intensity to Duration of Stimulation in Our Sensations of Light,' *PSYCHOLOGICAL REVIEW*, 1896, 3, pp. 484-492.

⁵ Dürr, E., 'Ueber das Ansteigen der Netzhauterregung,' *Philosophische Studien*, 1901-1903, 18, pp. 215-273.

⁶ Martius, G., 'Ueber die Dauer der Lichtempfindungen,' *Beiträge zur Psychologie und Philosophie*, Leipzig, 1902, 1, Heft 3.

⁷ Broca, A., and Sulzer, D., *Comptes Rendus des Séances de l'Académie des Sciences*, 1902, 134, pp. 831-834; 1903, 137, pp. 944-946; 977-979; and 1046-1049.

⁸ McDougall, W., 'The Variation of the Intensity of Visual Sensation with the Duration of the Stimulus,' *British Journal of Psychology*, 1904-1905, 1, pp. 151-189.

⁹ Büchner, M., 'Ueber das Ansteigen der Helligkeitserregung,' *Psychologische Studien*, 1906-1907, 2, pp. 1-29.

colored and colorless sensations; and, for comparative purposes, the average exposure time that was used in our experiments for all the colors in the determination of their brightness by the method of flicker. In choosing this time of exposure for the method of flicker, in order to secure for the method the greatest possible sensitivity, we used the slowest rate of succession of colored and colorless sectors that could be employed.

An inspection of this table will show that while the results for the development time of sensation differ quite a little among themselves, they agree in one very important particular, namely, they are all much greater than are the intervals that are used in the longest exposures that are permissible by the method of flicker. That is, by the method of flicker, the eye is very much underexposed to its stimulus. The effect of this under exposure is obviously to cause a reduction in the intensity of sensation. That is, the rate of succession of impressions used in the method of flicker is too fast for the single impressions to arouse their maximum effect in sensation and too slow for the successive impressions to add or summate as much as they would need to do to cause the intensity of the sensation aroused by each light to rise to its full value, or perhaps even to rise to a higher value than would be given by the individual exposures. In fact as will be shown in an appendix to this paper the sensation can not be expected to rise to its full value through summation if the Talbot-Plateau law be true, however rapid is the rate of succession of the individual impressions (see appendix). Even when a rate is reached at which complete fusion takes place, both for the color and brightness components in sensation, there is according to the Talbot-

¹⁰ Berliner, 'Der Anstieg der reinen Farbenerregung im Sehorgan,' *Psychologische Studien*, 1907, 3, pp. 91-155.

W. Swan in an article entitled 'On the Gradual Production of Luminous Impressions on the Eye; Part II., being a description of an instrument for producing isolated luminous impressions on the eye of extremely short duration, and for measuring their intensity,' *Trans. Roy. Soc. Edinb.*, 1861, 2, pp. 33-40, has described a very ingenious but complicated apparatus for getting short periods of stimulation of the retina, but apparently neither he nor any one else has ever used the apparatus described.

Plateau law, a reduction in the intensity of each sensation which is the same as would be gotten were the intensity of each light to be reduced in proportion to the time of exposure of that light to the total time of exposure of both lights, and no further increase in the rate of succession produces any change in the effect.¹ The possibility then of the sensations which, as is shown by the work on development times, are unequal for the single exposures used in the method of flicker, reaching equality by rising to their full value seems to be ruled out. In terms of the Talbot-Plateau law they could not reach their full intensity through an effect of summation, however fast the rate of succession be made,

¹ Ewald ("Versuche zur Analyse der Licht- und Farbenreaktionen eines Wirbellosen" (*Daphnia pulex*), *Ztschr. f. Psychol. u. Physiol. d. Sinnes.*, 1914, 48, pp. 285-325; and "The Applicability of the Photochemical Energy Law to Light Reactions in Animals," *Science*, 1913, 38, pp. 236-238) has made an interesting contribution with regard to the effect of the intermittent action of light on the eye which it may not be out of place to mention here. The faceted eye of the daphnia was used in his experiments. When exposed to light this eye responds by turning towards the light, and when lights of different intensities are used it turns towards the stronger light. After having determined the sensitivity of this response to difference in intensity of light by exposing the eye to a number of lights of different intensities acting continuously on the eye, he undertook to make a comparison of the effect of light acting continuously and intermittently. The intermittence was gotten by rotating a sectored disc in front of one of the lights. The lights were so chosen that the same amount of energy acted upon the eye in a given unit of time from both the continuous and intermittent sources. That is if a ratio of total open to closed sector of the value $1/10$ was used, the light in front of which these sectors were rotated was made ten times as intense as the light acting continuously. The sectored disc was then rotated at different speeds. When a speed of 30 revolutions per second was attained the eye remained stationary. That is at this speed of rotation the two lights produced equal effects on the eye,—which is, of course, no more than a demonstration of the Talbot-Plateau law for the primitive eye. But when the speed was made slower than this, the eye invariably turned towards the light which was acting continuously. That is when the rate at which the impressions were given to the eye was made slower the result was to weaken the effect on the eye even though the same amount of light was received by the eye in a unit of time in both cases. Ewald's results show then that, so far as the primitive eye is concerned, when light impressions are given to the eye at certain high rates of succession (analogous to the fusion rates for the human eye) there is a reduction in the amount of response aroused which is the same as would be produced were the intensity of the light reduced by an amount proportional to the ratio of the time of exposure to the light to the total time of the observation; and when they are given to the eye at rates slower than these the effect on the eye is the same as if the light acting on it had been still further reduced in intensity.

let alone attain it at the rates which are employed in the method of flicker.¹

¹ There seems to be only one other possibility that the method of flicker should give the true photometric balance between lights of different color values, namely, that the sensations aroused should reach equality at some value lower than the full value. That this is extremely improbable is shown by the following consideration. The weaker sensation or the sensation which has the slower rate of development for a single exposure would have to rise in value because of summation effect resulting from the succession of exposures until it became equal to the stronger sensation. To produce any effect of summation each individual impression would have to last over in sensation until the next impression of its kind is received which, since the impressions alternate, would be the next impression but one. And to produce the particular effect required here, not only would each excitation have to last over until the next one is aroused, but the weaker one would have to last over more strongly than the stronger one, else the effect of the summation would not be to produce the gain of the weaker on the stronger which is required to bring the two to the true photometric balance. That is, the advocate of this point of view would say that even though for the single exposure one color is weighted more than the other, the effect of this is obliterated in a succession of impressions and the two rise to equal value, because the weaker sensation would carry over more strongly hence would gain more relatively in the process of summing than would the stronger sensation. This is not at all in accord with the experimental evidence available at this time on the relation of the positive after-effect or persistence of sensation to the original sensation. Goldschmidt ("Quantitative Untersuchungen über positive Nachbilder," *Psych. Studien*, 1910, 6, pp. 159-252) and others show, for example, that the stronger the original sensation, the more strongly does it tend to carry over after the light is cut off. Goldschmidt also concludes from his experiments, which is a very important point for this discussion, that the tendency of the sensation to carry over is, so far as its brightness is concerned, independent of the color. That is, suppose that a photometric balance was obtained for green and red lights of comparatively high intensities by the method of flicker. Then according to Broca and Sulzer's curves, also the results obtained in this laboratory, green would attain to a higher brightness value for the single exposure than would be attained by red. Hence if green is not to be overestimated by the method of flicker, red must carry over more strongly as the impressions succeed each other than does green, and thus make up by a summation effect the deficiency shown in the single exposure. But according to Goldschmidt's results this greater tendency to carry over could not be assumed for red, either because of its color value or because of its weaker intensity, and there is no other aspect of the sensation which could have any bearing on the question in hand. Moreover, this hypothesis is rendered still more untenable by the experimental fact that the situation at low intensities is reversed. That is, at low intensities red, as shown by the curves for difference in lag (see Fig. 2, p. 127), attains to a higher value than green for the single exposure. Then if red is not to be overestimated by the method of flicker and in direct proportion to the values given to the two sensations in the single exposure, green must be carried over more strongly in the succession of impressions than is red. The explanation of both of these points would require not only that the color value of the stimulus exerts an influence on the carrying over of the brightness aspect of the sensation, but that this influence reverses in passing from high to low intensities. For a discussion of how highly improbable it is for the rates of succession used in the method of flicker that one impression could last over until the next impression but one is received in any amount that could be of considerable consequence to the method, see appendix.

It seems fair to conclude, then, that instead of getting by the method of flicker the sensations that should be aroused by the lights with which we are working, we get sensations of lower intensity. But it may be asked what if there is a reduction of the intensity of the impressions received? Equalization is all we are working for and the intensity of both impressions is reduced. Is it not possible, therefore, to find a ratio of time of exposure to each light such that the amount of reduction in the intensity of both impressions will be equal? This would be comparatively simple if the rate of development for all the colored were the same as for all the colorless sensations. The intervals of exposure could be made equal as is ordinarily done when sectorized discs are used and as apparently must be done when the exposures are given by means of a rotating prism. But the development time for color sensation is not the same as for colorless sensation, and, moreover, the consensus of evidence is that the rate of development is not the same for any two of the color sensations. Thus from the standpoint of the unequal reduction in intensities produced by the method of flicker, the task of selecting a proper ratio of exposure time of colored to colorless light, in case of the different colors, is one that requires a great deal of accurate knowledge if the method is to have the sureness of principle needed,—more, the writers think, than we now possess.¹

¹One scarcely needs point out in this regard that there is apparently no point in the intensity scale for which a given reduction in intensity for colored light gives the same change in luminosity in sensation that it does for white light. Beginning with the spectrum of fully saturated colors and comparing the effect of reduction by equal amounts of colored and white lights equal in photometric value, the blues and greens are found not to decrease in luminosity so fast as the white light, and the reds and yellows are found to decrease faster. Or as the phenomenon is ordinarily expressed, there is a relative lightening of the blues and greens and a relative darkening of the reds and yellows. Nor is the phenomenon of unequal change confined to the lower intensities. It is more striking for these intensities, but it occurs also for the higher intensities. This conclusion is drawn from the statement made by several writers that beginning with the spectrum of fully saturated colors and increasing the intensity of light, all the colors are found to tend towards white, and in so doing to change their luminosities at different rates. (For example, see Helmholtz, H., 'Ueber Hrnn. D. Brewster's neue Analyse des Sonnenlichts,' *Pogg. Ann.*, 1852, 86, p. 520; also *Handbuch der physiologischen Optik*, zw. Aufl., 1896, pp. 465-466; Chodin, A., 'Ueber die Abhängigkeit der Farrbenempfindungen von der Lichtstärke,' *Sammlung physiologischer Abhandlungen von Preyer*, 1877, 1, p. 33 ff.; Brücke, E., 'Ueber einige

We have discussed here, moreover, the effect of underexposure at only one rate of rotation of the exposure apparatus. The situation becomes still more complicated when this rate is changed. If it were changed, as it must be to preserve the sensitivity of the method in passing from high to low illumination, the whole scale of magnitude of the underexposure would change, and a shift in the relative evaluation of the luminosities of the different colors might very well be expected from the shape of the sensation curves as they rise to their maximum. In fact this shift is found in the work of previous investigators¹ who have made the comparison at

Empfindungen im Gebiete der Sehnerven,' Sitzungsber. der Wiener Akademie, Math.-Natur. Klasse, 1878, 77, Abth. 3, p. 63.) As we have already stated, however (p. 113), we do not mean to draw too close an analogy here between the effect on the brightness of sensation produced by keeping the intensity of light constant and reducing the time of exposure of the eye to the light, and the effect of keeping the time of exposure of the eye to the light constant and reducing the intensity. The degree to which the analogy holds can scarcely be considered as fixed until more work is done showing the way in which the luminosity curves for the different colors rise to their maximum as the time of exposure of the eye to the different colored lights is increased.

¹ See, for example, the phenomenon called by Ives the "reverse Purkinje" effect (*Philos. Mag.*, 1912, 24, Ser. 6, pp. 170-173); later demonstrated and discussed by Luckiesch (*Electrical World*, March 22, 1913, p. 620). These writers have found that the red end of the spectrum shows a relatively higher luminosity value as compared with the green end by the method of flicker at low than at high illuminations. From the shape of Broca and Sulzer's curves for the rise of visual sensation, to its maximum, for example, this result might very well be due to the difference in the relative luminosity value of the colors caused by the difference in the length of exposure given to the eye in the method of flicker at the faster rates of speed required for the higher illuminations and at the slower rates for lower illuminations. That is, the longer exposures given by the slower speeds of rotation allow the colors to attain a higher intensity. For example, the speeds used by Ives for what he calls 10 Illumination Units range, for the different colors for five observers, from 7 to 10 cycles per second, and for 250 Illumination Units from 10 to 22 cycles per second.

Broca and Sulzer's curves (Fig. 1) are appended here for one order of intensity of stimulus (*Comptes Rendus*, 1903, 137, p. 978. For other intensities see p. 945). The curves given were selected because they alone show a comparison between the results for colored and white light. It will be seen from these curves that for exposures less than .07 sec. (approximate value), blue and green rise to a higher value than red; for exposures ranging from .07 to .11 sec., blue rises to a higher value than red, and red higher than green; and for exposures ranging from .11 sec. to about .25 sec., red rises to a higher value than blue or green.

There is also a very strong probability that the relative lag in sensation for the different wave-lengths is not the same for lights of low intensity as for lights of higher intensities. In fact the results that have been obtained so far in this laboratory in determining the development time of the sensations aroused by red, yellow, green, and

intensities low enough to necessitate a decided reduction in speed of rotation. And that the shift is different from the normal effect on the brightness of the colors produced by a decrease of illumination, is shown by the fact that according to the results of these investigators it is in a different direction from that given by the equality of brightness method. Moreover, in the later paper it will be shown that a change in this evaluation amounting to several times the smallest difference in luminosity that can be detected by the method, is also produced by working the reverse variation, that is, by keeping the rate of rotation constant and changing the ratio of value of colored to colorless sector. It is difficult, therefore, to avoid the conclusion that the type of exposure used in the method of flicker is an important factor in the cause of its disagreement with the results obtained by other methods.

blue lights of spectrum purity show that at low intensities red and yellow rise more rapidly in photometric value than green and blue. This result is quite marked in those parts of the curves representing an exposure time of the same order of magnitude as is used in the method of flicker. In order to show this point we have appended here

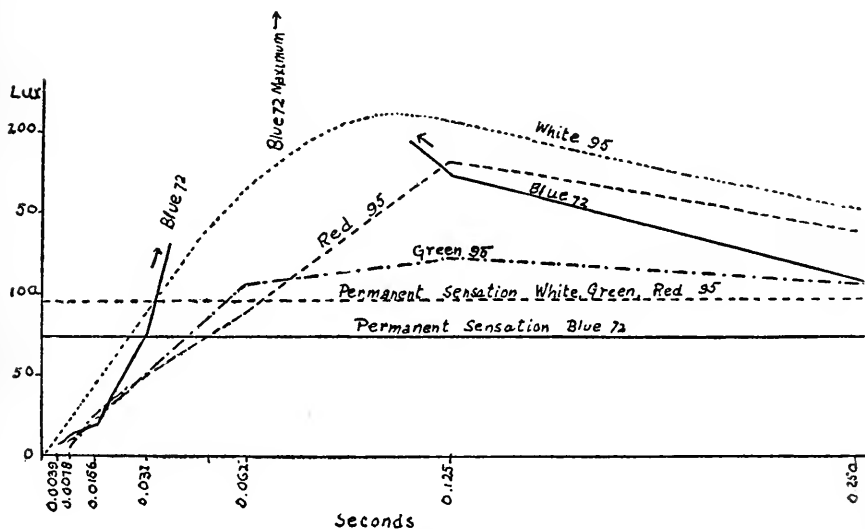


FIG. 1

three curves representing the relative rates of development of red, yellow, green, and blue at intensities which we will designate for the present as low and intermediate; and of red, yellow, and green for a higher intensity. These determinations were made by

Reëxamining the case, then, with regard to the underexposure of the eye by the method of flicker, we find that the short exposure times necessary to the method cause a re-

M. A. Bills of this laboratory. Later, results will be given for red, green, blue, and yellow at a number of intensities, and specifications will be made of the intensities employed in both photometric and radiometric units. The colored lights used in determining the curves given below were obtained from a spectrum of good definition and were in each case equal in photometric value, as they should be if results are to be used in interpreting the action of light on the eye under the conditions imposed by the

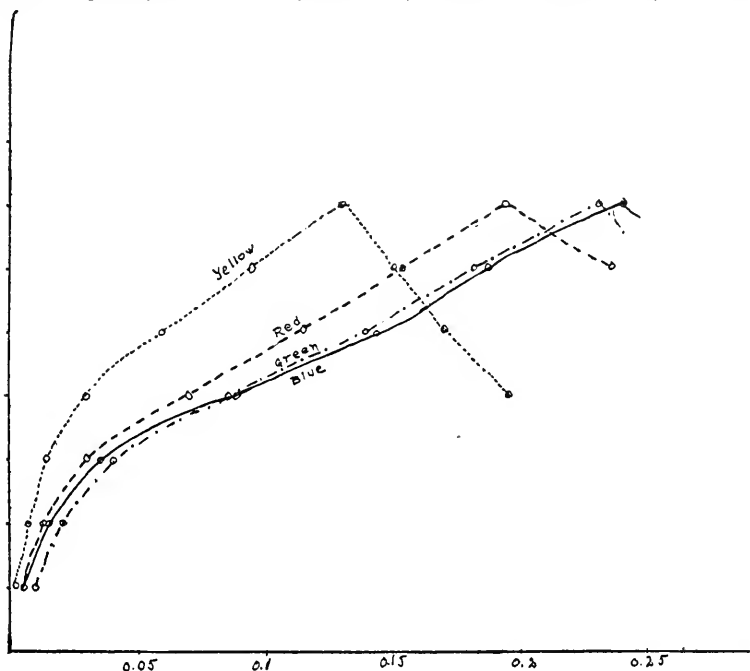


FIG. 2

method of flicker when the photometric balance is attained. In constructing these curves time of exposure is plotted along the abscissa and brightness of color along the ordinate. The curves in Fig. 2 are for the low intensity; in Fig. 3 for the intermediate intensity; and in Fig. 4 for the higher intensity.

It is very probable that there is considerable individual difference in the amount and distribution of lag. A rigid test of the correspondence of difference in lag to the direction of deviation of results gotten by the method of flicker from those obtained by the equality of brightness method would require that the photometric determinations and the determination of lag should be made for a given quality and intensity of light by the same observer.

If it should be found that there is an individual difference in the amount and distribution of lag, the result would supplement very nicely the explanation why a much higher degree of reproducibility is gotten by the method of flicker than by the method

duction in the action of the standard and comparison lights on the eye. If this reduction were equal in amount, quite enough difficulty would be encountered. But it is not of equality of brightness only when the results of a single observer are considered (see footnote, p. 115). That is since the factor of color difference which so disturbs the judgment in the equality of brightness method is eliminated in the method of flicker, we should get correspondingly a higher degree of reproducibility for a single observer and for different observers, were there not some factor present in the method of flicker and not in the equality of brightness method, which varies from individual to individual. So supplemented the explanation would be as follows. In the method of flicker the

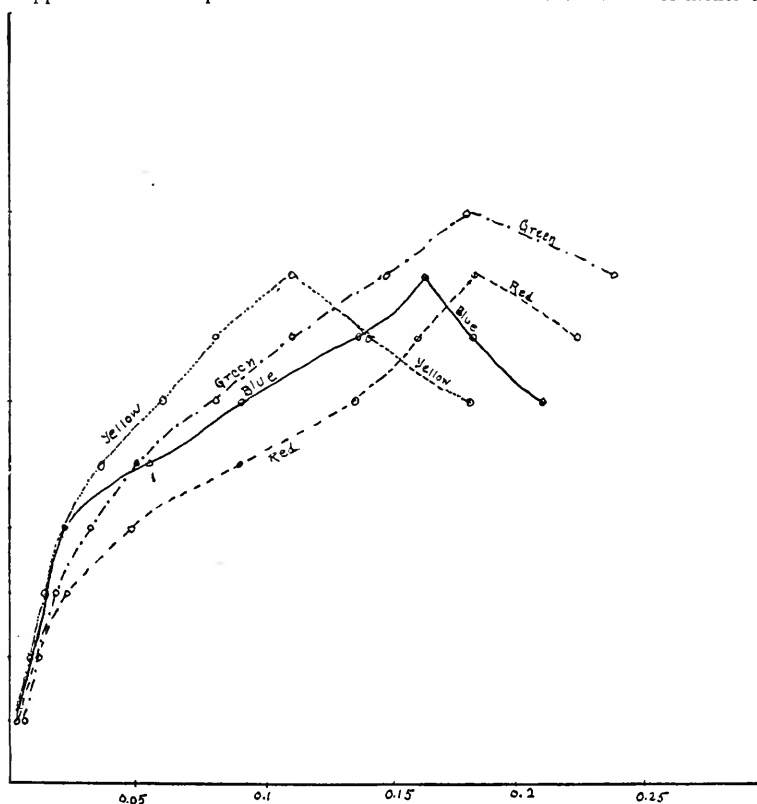


FIG. 3

judgment for a single observer shows a higher degree of reproducibility than in the equality of brightness method because of the elimination of the disturbing factor of color difference; but a false balance is established by the method, the deviation from the true balance depending in direction and amount for different observers upon the difference in the amount and distribution of lag in the rise of the sensations towards the maximum. The difference in the amount and direction of this deviation from the true balance from observer to observer is the cause of the relatively low degree of reproducibility of results when the work of different observers is compared.

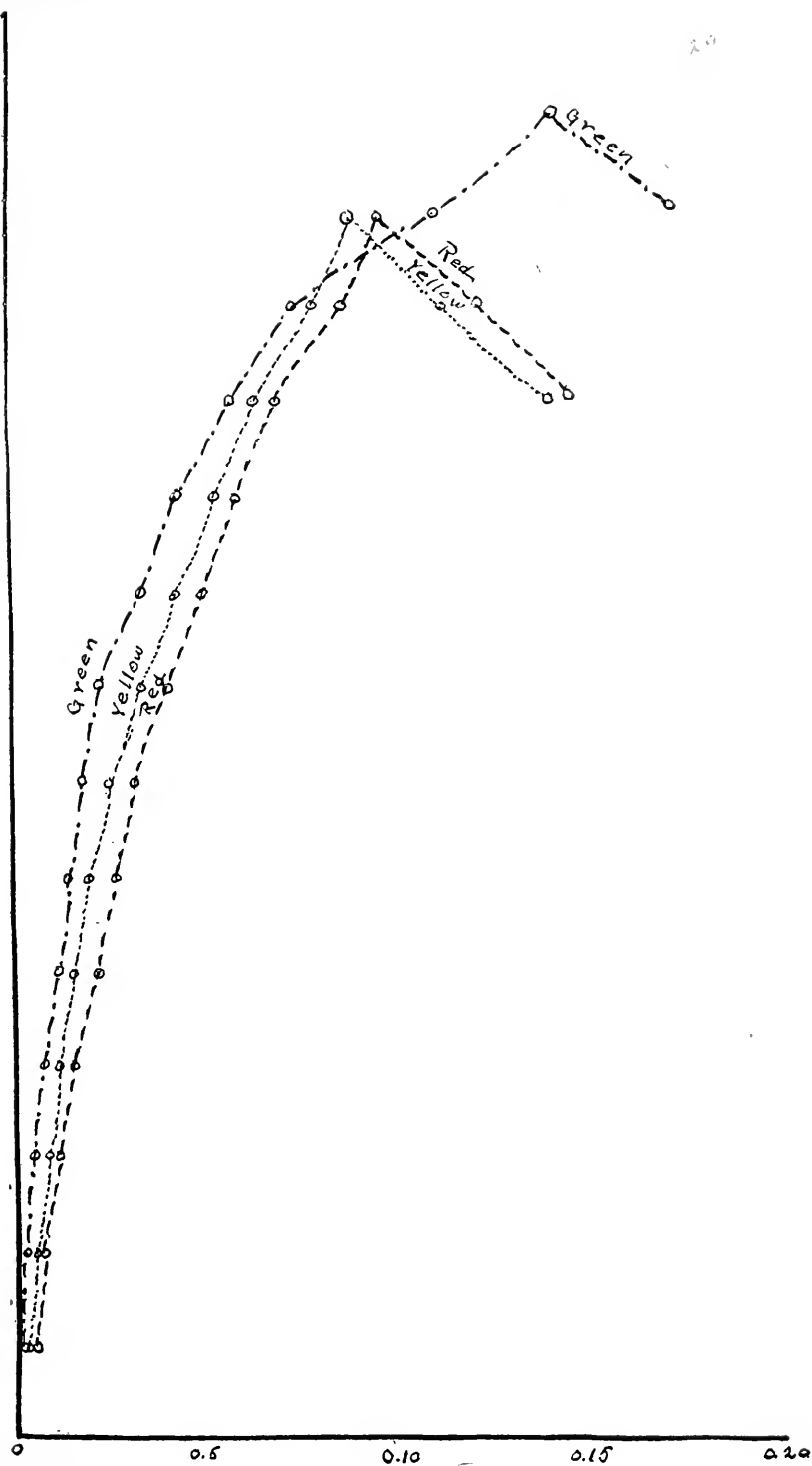


FIG. 4

equal in amount, and we have no adequate information as to the amount of the inequality. Until we have more information with regard to the amount of the reduction and the effect it produces, any successful attempt to regulate the relative duration of the exposure to colored and colorless light, even for a single color at a single intensity, can scarcely be more than the result of chance. Surely to expect to accomplish this for all intensities of all colors by a single ratio of exposure, more especially by means of a 1:1 ratio, as has been the practice in the past, is, it would seem to the writers, to ignore the sensation principles which underlie the method. Obviously this ratio requires calibration, and to give the method the sureness of principle required, it would seem that the calibration might have to be made for each color at the particular intensity at which the work is to be done. This calibration might possibly be accomplished by means of an accurate knowledge, if that knowledge could be secured in sufficient detail, of the temporal course of visual sensation as it rises to its maximum for the given intensity of light used; or it might be done by comparing the results obtained by the method of flicker with the results obtained by some other method adopted as a standard. So far the tendency seems to have been to look for this standard within the subject of photometry itself. As has already been stated, several writers have signified a desire to make the equality of brightness method a standard, and comparisons have been made of the results obtained by the method of flicker and the equality of brightness method.

A consideration of the results of these comparisons together with the data collected by one of the writers in ten years use of the flicker and equality of brightness methods in making the brightness matches needed for the work in color sensitivity, has influenced us to open the question anew in the interests of the work on color sensitivity. In the work with these two methods all done at comparatively high illuminations and with a large number of observers, agreement has been rare. For this reason the chief incentive to make the present study has not been to establish disagreement, but to investigate

further the causes of disagreement. The results of this study seem to indicate that the type of exposure of the eye to its stimulus by the method of flicker is an important cause of disagreement.

So much for the theoretical considerations relating to the method of flicker. To test the accuracy of some of the more important points that have come up, a plan of experimentation has been formulated and in part carried out. So far as the results of that experimentation will be reported upon in this paper, the following things will be shown. (1) By comparing the time required for the sensations aroused by colored and colorless light to reach their maximum of intensity, we have already shown that as a general case the eye is very much underexposed to its stimulus by the method of flicker, and we have concluded that the effect of this underexposure on the brightness component of sensation will be unequal in amount for colored and colorless light, and should lead, therefore, to a false estimation of the brightness of the colors. That this conclusion is justified so far as our work is concerned, will be demonstrated in part by comparing the results of the method of flicker with those obtained by the equality of brightness method, in which case the eye is fully exposed to its stimulus, and showing that for the method of flicker there is for our observers for the intensities of light used and for the rate of rotation of the photometer head required for these intensities, a characteristic underestimation of the brightness of red and yellow and overestimation of the brightness of blue and green. That this characteristic deviation is due to the type of exposure used in the method of flicker and not to some other factor will be further shown in the consideration of our second point. (2) We have said that the ratio of the time of exposure should be considered as a factor influencing the results obtained by the method of flicker. In order to confirm this judgment of the case, we have varied this ratio, keeping the other conditions constant, and have found that a corresponding variation is produced in the results. That is, by changing the value of the colored and colorless sectors in the rotating disc we have used to

regulate the time of exposure in the method of flicker, corresponding variations are obtained in the characteristic underestimations of red and yellow and the overestimations of blue and green. These variations, it will be shown, moreover, are very much greater than the changes in luminosity that are required to be detected by the method of flicker, and are, therefore, worthy of being taken into account in an evaluation of the usefulness of the method, whatever method be adopted as a standard for comparison. And (3) we have contended that if the equality of brightness method be adopted as the standard for work in color photometry, the method of flicker does not satisfy the requirements, for it does not give results which agree in the average with those obtained by the equality of brightness method. This will be shown both from results of our own work and from a preponderance of the work done by others who have made the comparison. In our own work the comparison has been made for a series of intensities which may be considered as at least fairly representative of the higher intensities, they being considered more favorable to agreement by Dr. Ives.¹ Especial care has been taken in this series to duplicate at one point the intensity which Dr. Ives finds the most favorable to agreement.

The remainder of the paper will be taken up with the demonstration of these three points.

I. THE UNDERESTIMATION OF THE LUMINOSITIES OF RED AND YELLOW AND THE OVERESTIMATION OF THE LUMINOSITIES OF BLUE AND GREEN

Special tables have not been prepared for this point because the results can readily be seen in the tables for points II. and III. In these tables taken collectively the comparison will be shown for a representative series of variations, both of the ratio of the time of exposure to colored and colorless light and of the intensity of the lights employed. In every case underestimation is found to be characteristic for red and yellow, and overestimation for blue and green.

¹ Ives, H. E., 'Studies in the Photometry of Lights of Different Colors, *Philos. Mag.*, 1912, 24, Ser. 6, pp. 149-188.

II. THE VARIATION OF THE RATIO OF THE TIME OF EXPOSURE
TO THE COLORED AND COLORLESS LIGHT CAUSES A
CORRESPONDING VARIATION IN THE CHARACTERISTIC
UNDERESTIMATION OF RED AND YELLOW AND
OVERESTIMATION OF BLUE AND GREEN

As has already been stated, the work under this heading has been undertaken in part to show the preceding point, and in part to show that the amount of this underestimation and overestimation is a variable function of the ratio of the time of exposure to the colored and the colorless light. The effect of the variation was determined both when the comparison was made between colored and colorless pigment surfaces, and between colored and colorless lights. For the pigment surfaces the standard red, green, blue, yellow, white, and black of the Hering series of papers were used. For the colored lights, two sources have been used: the Wratten and Wainwright color filters, and the light of the spectrum. Since the work with the spectrum as source has not yet been finished, results will be given at this point from the work with the filters. Of these filters, only the *Alpha* and *Eta* were used. The former transmits a band of red from the end of the spectrum to $.65 \mu$, the latter, a band in the blue-green from $.52 \mu$ to $.465 \mu$. These two alone were used for the following reasons: (1) They are fairly representative of the colors that show a relative change in luminosity with change of intensity. And (2) the yellow, green, and blue filters each transmits components that undergo opposite luminosity changes with a change of intensity of the source. That is, the best yellow of the series transmits also a green component; the best green, a yellow component; and the best blue transmits some of the violet.

The photometric apparatus employed was for the sake of comparison made to conform very closely in its essential features to that described by Dr. Ives.¹ The general plan of our apparatus is indicated in Fig. 5. It consists of a photometer bar carrying the standard white light (*A*), a second bar carrying the colored light (*B*), a sector disc (*C*), and a

¹ Ives, H. E., *op. cit.*, p. 161.

screen (*D*) provided with a small aperture (*O*) through which the light comes to the eye. The standard white light was enclosed in a black light-proof box (*E*), which was provided

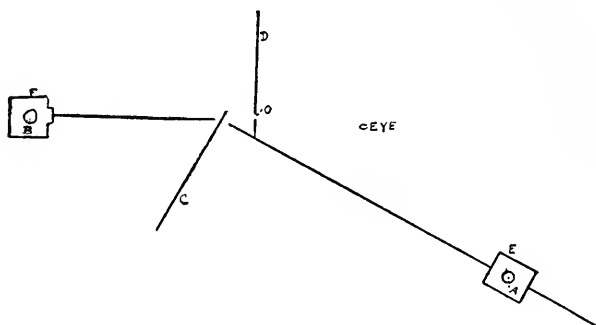


FIG. 5

in front with a circular opening 4 cm. in diameter for the transmission of the light. In passing to the sectorcd disc, the light was screened both from the observer's eye and from the colored source by black screens properly placed. The light which was passed through the colored filters was placed in a similar light-proof box (*F*) provided with an opening 4 cm. square for the transmission of the light. Above and below this opening were grooves into which the color filters were slid. The sectorcd discs were made of aluminum. The edges of these discs were carefully bevelled and the surface was kept freshly covered with magnesium oxide deposited from the burning metal. The aperture in the screen through which the light passed to the observer's eye was 3 mm. square. The visual angle subtended by this aperture at the observer's eye at 20 cm. distance was very small. A small angle was needed to guard against the unequal sensitivity of the central and paracentral portions of the retina to flicker, and against the difference in their brightness sensitivity to colored and colorless light. A 13-candle-power Mazda lamp was used as source for the colorless light, and 13-cp., 52-cp., and 130-cp. lamps for the colored light. These lamps were operated on a 110 D.C. circuit in series with an ammeter and finely graduated rheostat to guard against fluctuations in the current and

loss of efficiency in the lamps. Also fresh lamps were substituted at the beginning of each series of observations. As a check on the results obtained from these lamps, several series of observations were made using a standardized tungsten lamp, street series, 16.6-cp. operated at 11.43 volts by a storage battery for the colorless light, and a similar lamp of 67-cp. operated by a storage battery at 10.35 volts for the source of the colored light.

The method of making the flicker judgment was as follows: A preliminary determination was made of the approximate setting of the light which was being moved, to give equalization. The speed of rotation of the sectored disc was then reduced until flicker was obtained. The position of the light was again adjusted until no flicker was obtained, and so on. This variation in the speed of rotation of the disc and the position of the light was continued until the position was ascertained that gave no flicker for the lowest speed of rotation. The final determination of this point was made by moving the light in both directions until noticeable flicker was obtained, and taking the average of these two readings. The movement required to give flicker on either side of this average position ranged usually from 2 to 9 mm. depending to some extent upon the observer and the intensity of illumination used. Employing the above apparatus and method, results were obtained for the highest intensity of colored light used for a total open sector of 315° , 270° , 225° , 180° , and 45° ; and for the other intensities, for a total open sector of 315° , 180° , and 45° . In making the comparisons by the equality of brightness method, the disc was rotated until one of its edges bisected horizontally the photometric field. The results are shown in Tables II.-V. They will be summarized briefly as follows: (1) For all values of open sector and for all intensities of light, there was an underestimation of the luminosity of the red light and an overestimation of the luminosity of the blue-green. (2) As the size of the open sector was decreased, there was a corresponding increase in the amount of the underestimation of the luminosity of the red for all the intensities employed, and of the overestimation

TABLE II
OBSERVER A

Showing that the Underestimation of Red and the Overestimation of Blue-green is a Characteristic of the Method of Flicker, for Lights of the Intensity Used in this Work, and that the Amount of this Underestimation and Overestimation is a Variable Function of the Ratio of the Time of Exposure of the Eye to the Colored and the Colorless Light

Source of White Light	Source of Colored Light	Color	Equality of Brightness Method	Flicker Method		Difference by Equality of Brightness Method and by Flicker Method with 180° Open Sector	Change Produced by Varying Sectors	Amount of Change that Can be Detected by		No. of Revolutions per Second, Flicker Method
				Value of Colored Sector	Distance of White Light Giving no Flicker			Equality of Brightness Method	Flicker Method	
13 cp.	13 cp. 151 cm. distant from photometric screen	Red	125.5 cm.	315° 180°	133.9 cm. 135.9	-10.4 cm.	-3.4 cm.	3.5 cm.	.4 cm.	3.6 4.7 4.1 4.2 6
		Blue-green	191	45° 315° 180°	137.3 183.45 180.45	+10.55	+5.4	4	.3 .35 .35	4.1 4.2 6
		Red	93.4	45° 315° 180°	178.05 102.05 104.5	-11.1	-4	3	.25 .25 .2	5.2 3.7 5.9
		Blue-green	103	45° 315° 180°	106.05 94.5 90	+13	+5.65	4	.25 .3 .35	5.4 4.1 6.1
		Red	75.3	45° 315° 270°	88.85 82.9 84	-9.7	-4	3	.45 .4 .5	5.9 6.3 7.4
	130 cp. 89 cm. distant from photometric screen	Blue-green	82	225° 180°	84.6 85	+7	+3.25	3.5	.5 .5 .3 .3 .35	9.2 9.2 8.9 6.6 7.4
		Blue-green		45° 315° 270°	86.9 76 77					8.9 6.6 7.4
		Blue-green		225° 180°	76.3 75					8.1 7.7
		Blue-green		45°	73.75					7
		Blue-green								

TABLE II.—Continued

OBSERVER A

Source of White Light	Source of Colored Light	Color	Equality of Brightness Method	Flicker Method.		Difference by Equality of Brightness Method and by Flicker Method with 180° Open Sector	Change Produced by Varying Sectors	Amount of Change that Can Be Detected by		No. of Revolutions per Second, Flicker Method
				Value of Colored Sector	Distance of White Light Giving no Flicker			Equality of Brightness Method	Flicker Method	
16.6 cp. standard lamp	67 cp. standard lamp, 89 cm. distant from photometric screen	Red	86.5	315°	96.1	-13	-4.2	2.5	.5	6.1
				180°	99.5					8.7
				45°	100.3					8.2
				315°	77.4		+5.4	3	.3	5.6
				180°	73.45					7.2
				45°	72				.45	6.9

TABLE III

OBSERVER B

13 cp.	52 cp. 151 cm. distant from photometric screen	Red	88 cm.	315°	99.18 cm.	-17.5 cm.	-8.82 cm.	3.5 cm.	.8 cm.	7.8
				180°	105.5					7.8
16.6 cp. standard lamp	67 cp. standard lamp, 89 cm. distant from photometric screen	Blue-green	98	45°	108	+7.4	+7.7	4	.85	10.9
				315°	96.2					7.4
		Red	86	180°	90.6	-15	-6.5	3	.8	7.2
				45°	88.5					6.15
		Blue-green	84.3	315°	96.5	+10.8	+8	4.3	.9	9
				180°	101					11.8
				45°	103				.85	11.4
				315°	78.5					5.3
				180°	73.5				.8	7.4
				45°	70.5				.85	7

of the blue-green. (3) The amount of change in the photometric value of the color produced by varying the ratio of exposure to colored and colorless light was many times the smallest amount of change that can be detected by the method of flicker, and, therefore, must be considered of consequence in relation to the application of the method to practical work.

Column 1 of these tables represents the source of white light; Column 2, the source of colored light; Column 3, the color used; Column 4, the distance of the white light from the disc when judgment of equality is given by equality of brightness method; Column 5, the value of the colored sector for the method of flicker; Column 6, the distance from the disc at which the white light has to be placed to give the judgment of no flicker; Column 7, the difference in the distance the white light was placed for the equality of brightness method and the flicker method with 180° of colored sector; Column 8, the change in the distance of the white light produced by varying the value of the colored sectors in the method of flicker; Column 9, the distance the white light has to be moved in the equality of brightness method to change the judgment from equality to just noticeably lighter or darker; Column 10, the distance the white light has to be moved in the flicker method to change the judgment from no flicker to just noticeable flicker; and Column 11, the number of revolutions per second of the sectored disc for the method of flicker.

Tables IV. and V. represent the results of Tables II. and III. expressed in percentage of luminosity at the photometric screen.

Pigment papers are still used in a great many laboratories for the investigation of color sensitivity, and because of their convenience and ease of manipulation, they probably will be used for many years to come for preliminary work and for a certain class of investigations in which only comparative results are wanted. In estimating the brightness or luminosity of these pigment colors, the method of flicker is now much more extensively used perhaps than any of the other methods of making brightness comparisons. For this reason we have considered it worth while to extend our work to the

TABLE IV

OBSERVER A

Showing the Results in Table II. Expressed in Percentage of Luminosity

Source of White Light	Source of Colored Light	Color	Disagreement Between Equality of Brightness Method and Flicker Method with 180° Open Sector	Change Produced by Varying Sectors	Amount of Change that Can Be Detected by	
					Equality of Brightness Method	Flicker Method
13 cp.	13 cp. 151 cm. distant from photometric screen	Red	-15 %	- 4.8%	5 %	.4%
		Blue-green	+12.3	+ 6.3	3.7	.6
	52 cp. 151 cm. distant from photometric screen	Red	-20	- 7.5	7	.4
		Blue-green	+30	+13	7.3	.6
16.6 cp. standard lamp	130 cp. 89 cm. distant from photometric screen	Red	-21	- 9	7	.9
		Blue-green	+19.7	+ 7.3	6.8	.7
	67 cp. standard lamp, 89 cm. distant from photometric screen	Red	-23.6	- 8.3	8.7	1
		Blue-green	+33	+ 8.3	8.5	.8

TABLE V

OBSERVER B

13 cp.	52 cp. 151 cm. distant from photometric screen	Red	-30%	-16%	7.5%	1.7%
		Blue-green	+17.	+18	7.7	1.2
16.6 cp. standard lamp	67 cp. standard lamp, 89 cm. distant from photometric screen	Red	-28.	-12.4	6.5	1.6
		Blue-green	+31.7	+24.	9	2

investigation of the effect of varying the value of the colored and the colorless sectors on the brightness of the pigment colors as determined by the method of flicker. Of the devices available for applying the method to these colors, the Schenck apparatus was selected as best suited to our purpose. As colors to be investigated, the red, green, blue, and yellow of the Hering series of standard papers were chosen. Sectors of the value of 180°, 270°, and 300° were used. Values lower

than 180° were not used because they could not be accurately obtained with the type of photometer employed. Two intensities of illumination were used, one of 390 foot-candles (vertical component) received directly under a skylight and diffusion sash of ground glass; the other, 5 foot-candles, the illumination of a room lighted by windows. Space will be given here only for the results for the higher illumination. This illumination was carefully chosen far above the range of intensities at which the Purkinje phenomenon occurs when the eye is fully exposed to its stimulus, in order to subject our demonstration to a rigid test. We were seeking, for example, to ascertain whether an intensity might not be found so high that the underexposure of the eye to its stimulus by the method of flicker would not cause an underestimation of the brightness of red and yellow and an overestimation of the brightness of blue and green.¹ That these underestimations and overestimations occur at this high illumination and by amounts many times the smallest brightness difference that can be detected by the method, will be shown in Table VI.

Column 1 of this table shows the color used; Column 2, the black-white value of the color estimated by the equality of brightness method; Column 3 gives the value of the colored sector; Column 4, the white-black value of the color estimated by the flicker method; Column 5 gives the difference in the result by the equality of brightness and flicker method with 180° colored sector; Column 6 gives the change produced in the result by the method of flicker by varying the size of the colored sector; Column 7 gives the amount of change that can be detected by the equality of brightness method; and Column 8, by the flicker method.

III. THE METHOD OF FLICKER DOES NOT GIVE RESULTS WHICH AGREE IN THE AVERAGE WITH THOSE OBTAINED BY THE EQUALITY OF BRIGHTNESS METHOD

Nothing will be added in this section except to make our comparisons at the intensity of illumination found to be most

¹ We have been careful to choose high intensities because Dr. Ives has contended that at high intensities the disagreement between the methods of flicker and equality of brightness tends to disappear.

TABLE VI

OBSERVER A

Showing that the Underestimation of Red and Yellow and the Overestimation of Blue and Green is a Characteristic of the Method of Flicker for Light of the Intensity Used in this Work, and that the Amount of this Underestimation and Overestimation is a Variable Function of the Ratio of the Time of Exposure of the Eye to the Colored and the Colorless Light.

Color	Equality of Brightness Method	Flicker Method		Difference by Equality of Brightness Method and by Flicker Method with 180° Colored Sector	Change Produced by Varying Sectors	Amount of Change that can be Detected by	
	White-black Value	Value of Colored Sector	White-black Value			Equality of Brightness Method	Flicker Method
Red	White 64° Black 296°	300°	White 58.9° Black 301.1°	-17.4°	-12.3°	8°	1.8°
		270°	White 56.2° Black 303.8°				1.2°
		180°	White 46.6° Black 313.4°				1.8°
Yellow	White 332° Black 28°	300°	White 328.3° Black 31.7°	-18.6°	-14.9°	9.5°	2°
		270°	White 321.7° Black 38.3°				1.8°
		180°	White 313.4° Black 46.6°				1.8°
Green	White 88.5° Black 251.5°	300°	White 99° Black 261°	+26.4°	+15.9°	9°	.45°
		270°	White 105.5° Black 254.5°				.9°
		180°	White 114.9° Black 245.1°				.45°
Blue	White 12.5° Black 347.5°	300°	White 14.5° Black 345.5°	+10.7°	+8.7°	5.3°	2.2°
		270°	White 19.1° Black 340.9°				1.4°
		180°	White 23.2° Black 336.8°				.9°

favorable for agreement by Dr. Ives.¹ The plan of the apparatus used in this work is indicated in Fig. 6. A spectro-scope was used to give the colored light; a 32-cp. carbon lamp (*F*) was used as the source of the colorless light. This lamp gave a light of the same quality as that used by Dr. Ives, namely, the quality of the carbon standard of 4.85 watts per mean spherical candle. When placed at 32.6 cm. from the sectorized disc (*D*), 270 meter candles of light were reflected

¹ Ives, H. E., *op. cit.*, p. 173.

from the disc. The eye piece was removed from the spectro-scope and a lens system was used in its place consisting of two lenses (*A*) and (*B*), one to render the light emerging from the objective slit (*C*) parallel, and the other to focus it on the eye 30 cm. distant. Between the eye and the focusing lens (*B*) was interposed the sectorcd disc (*D*). Thus the light reflected from the sectorcd disc suffered no absorption in passing to the eye. A stimulus-opening (*E*) 16 mm. in diameter was placed in front of the disc 20 cm. from the eye. This subtended the

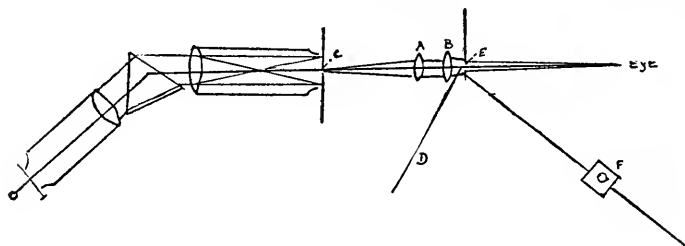


FIG. 6

same visual angle as the field size that Dr. Ives found to be the most favorable. A pupillary aperture 1 mm. square placed in front of the eye reduced the light reflected from the white disc to the intensity called by Dr. Ives 270 illumination units.¹ The colors used were a very narrow band of the spectrum in the region of $.68 \mu$, $.57 \mu$, $.52 \mu$, and $.47 \mu$, giving the four pure colors red, yellow, green, and blue. The method of making the comparison was as follows: The sectorcd disc was turned so that its edge bisected horizontally the photometric field, and the luminosity of the colored field was altered by changing the width of the collimator-slit until it equalled by the equality of brightness method the 270 illumination units. Using this slit width, then, the disc was rotated and the position of the white light was adjusted until no

¹ By using a pupillary aperture 1 mm. square, Dr. Ives has reduced the light entering the eye by an amount which, so far as we can see, can not be determined. He has established an arbitrary unit which he calls an illumination unit. We can not, therefore, compare the intensities of light used by us in the preceding experiments (pp. 134 ff.) with the 270 illumination units used by Dr. Ives. If one were to judge, however, by the apparent brightness of the disc in the two cases, he would have to say that the amount of light entering the eye was considerably greater for our

flicker was obtained. The flicker determinations were made with 315° , 180° , and 45° total open sector as before. The results are shown in Tables VII and VIII.

TABLE VII

OBSERVER *A*

Showing that the Underestimation of Red and Yellow and the Overestimation of Blue and Green is a Characteristic of the Method of Flicker for Lights of the Intensity Used in this Work, and that the Amount of this Underestimation and Overestimation is a Variable Function of the Ratio of the Time of Exposure of the Eye to the Colored and the Colorless Light. Intensity same as was used by Ives

Wave-length	Equality of Brightness Method	Flicker Method		Difference by Equality of Brightness Method and by Flicker Method with 180° Colored Sector	Change Produced by Varying Sectors	Amount of Change that Can Be Detected by		No. of Revolutions per Second, Flicker Method
	Distance of White Light Giving Equality of Illumination	Value of Colored Sector	Distance of White Light Giving no Flicker			Equality of Brightness Method	Flicker Method	
.68 μ	32.6 cm.	315°	41.5 cm.	-11.6 cm.	-3.6 cm.	2.4 cm.	.5 cm.	9.2
		180°	44.2				.45	12
		45°	45.1				.5	11
.57 μ	32.6	315°	37.4	- 6.9	-3.4	2.8	.4	9.8
		180°	39.5				.4	14
		45°	40.8				.4	12
.52 μ	32.6	315°	23	+13.6	+4.9	2	.5	9.7
		180°	19				.4	13
		45°	18.1				.4	11.7
.47 μ	32.6	315°	23	+13.8	+5	2.3	.45	9.9
		180°	18.8				.4	14.1
		45°	18				.45	12

higher intensities than the 270 illumination units used by Dr. Ives. Thus it seems probable that most of our preceding tests were made with an intensity of light equal to or greater than that used by him. His claim, it will be remembered, was that one of the two causes of disagreement between the results obtained by the methods of flicker and equality of brightness in preceding experiments is the low intensity of the lights used. (The other was the lack of proper regulation of the size of the photometric field.) We do not believe that either one of these factors is the fundamental cause of disagreement, as is attested in our experiments by the fact that strong disagreement remains when both of them have been eliminated, at least, as completely as they were eliminated by Dr. Ives. A consideration of the functioning of the eye under very short exposures to light, shows, we believe, a much more fundamental cause of disagreement, namely, the difference in the way in which the eye responds to light stimuli when presented for the lengths of time used in the two methods.

TABLE VIII

OBSERVER B

.68 μ	32.6	315°	41.3	-11.6	-4	3	.8	12
		180°	44.2				.7	14
		45°	45.3				.8	13.4
.57 μ	32.6	315°	38	- 8.9	-4.3	2.9	.9	12.5
		180°	41.5				.6	14.2
		45°	42.3				.8	13.1
.52 μ	32.6	315°	23.4	+12.1	+3.9	3.3	.8	12
		180°	20.5				.7	14
		45°	19.5				.7	12.2
.47 μ	32.6	315°	22.8	+12.6	+4	3.5	.9	11.1
		180°	20				.7	14.4
		45°	18.8				.8	12.8

It was stated in the beginning of the paper that disagreement between the results of the method of flicker and equality of brightness would be shown from a preponderance of the work done by others who have made the comparison. As a general case the fact scarcely needs more than the pointing out. Before the work of Ives, disagreement was pretty generally admitted. Bell¹ says: "That the flicker and equality of brightness methods do not give coincident results when we consider the general case of flicker photometers, as compared with equality of brightness photometers, is a fact that has been too long familiar to photometrists to admit of a discussion." Comparisons of the two methods have been made by Whitman, Wilde, Dow, Bell, Stuhr, Luckiesh and Ives. Whitman² compared the luminosities of a red and green light placed 6 ft. apart on a photometer bar. He found that the setting of the photometer for equality of illumination differed for the equality of brightness and flicker methods by 1.2 ft. for one observer, and .8 ft. for another. Wilde³ photometered a tungsten lamp against a carbon by the methods of flicker and equality of brightness, and found a difference of 6 per cent. in the result. Bell⁴ compared the ratio of lumin-

¹ Bell, L., 'Acuity in Monochromatic Light,' *Electrical World*, Sept. 9, 1911, 58, p. 637.

² Whitman, F. P., 'On the Photometry of Differently Colored Lights and the Flicker Photometer,' *Physical Review*, 1896, 3, pp. 241-249.

³ Wilde, L. W., 'The Photometry of Differently Colored Lights,' *The Electrician*, July 16, 1909, 63, pp. 540-541.

⁴ Bell, L., 'Chromatic Aberration and Visual Acuity,' *Electrical World*, May 11, 1911, 57, pp. 1163-1166.

osities of a mercury vapor lamp with that of a tungsten lamp by means of the flicker method and found it to be 5.42. These same lights by the equality of brightness method gave a ratio ranging from 6.86 to 10.93 for different observers. Stuhr¹ compared red and green lights by several methods including the method of flicker and equality of brightness. He found that the mean deviation of the values obtained by the method of flicker from those obtained by the equality of brightness method amounted to 14.14 per cent. Luckiesh² photometered a red against a blue-green light by the methods of flicker and equality of brightness, and found a difference of 62 per cent. in the ratios of the luminosities of the two lights by the two methods.

Two factors have in the main been assigned to the cause of the disagreement: the effect of intensity and of size of the photometric field. Lauriol, Dow, Millar, Ives, and Luckiesh have investigated the former factor, and Schenck, Dow, and Ives the latter. These are both factors which affect the results of both methods. In comparison little attempt has been made to find the factors that affect the results of each method alone. As a general case these, it would seem, might be more apt to prove a source of disagreement than those which affect both methods.

With regard to the intensity of the light as a factor, Lauriol³ and Dow⁴ claim that the relative shift in the brightness of the different colors at low illuminations is shown by both methods. The shift for Dow, however, is more pronounced in the equality of brightness than the flicker determinations. For Lauriol the shift for the different colors varies in magnitude by the two methods and in some cases in direction. Millar,⁵ on the other hand, claims that the

¹ Stuhr, J., 'Ueber die Bestimmung des Aequivalenzwertes verschiedenfarbiger Lichtquellen,' Kiel, Philos. Diss., Vol. 19, Okt., 1908, p. 50.

² Luckiesh, M., 'Purkinje Effect and Comparison of Flicker and Equality of Brightness Photometers,' *Electrical World*, March 22, 1913, p. 620.

³ Lauriol, 'Le photomètre à papillotement et la photométrie heterochrome,' *Bull. Soc. Intern. des Électriciens*, 1904, pp. 647-652.

⁴ Dow, J. S., 'Color Phenomena in Photometry,' *Philos. Mag.*, 1906, 12, Ser. 6, p. 131.

⁵ Millar, P. S., 'The Problem of Heterochromatic Photometry,' *Trans. Illuminating Engineering Society*, 1909, 4, p. 769.

Purkinje phenomenon is not shown at all by the flicker method at low illuminations, while Ives¹ and Luckiesh² go to the other extreme and declare that a reverse Purkinje effect is obtained by the flicker method. With regard to size of field as a factor, Schenck³ found that a decrease in size lowered the mean variation for the flicker method and decreased the luminosity value obtained for all the colors. Dow⁴ found that as the size of the field was decreased, red and yellow lightened relatively to green and blue. This effect was more pronounced for the equality of brightness than for the flicker method. Ives⁵ found this effect for the equality of brightness method, but the reverse effect for the flicker method.

Ives, admitting the disagreement between the two methods and accepting size of field and intensity of the stimulus as the cause of the disagreement, sought to determine whether a field size and intensity could not be found for which the two methods agree. He photometered different portions of the spectrum against carbon lamps at a number of intensities and with a number of field sizes. He found in general for five observers that the luminosity curves obtained by each method differed. This difference, however, was less for high intensities than for low.

A table is appended (Table IX) in which is shown in percentage the difference in results gotten by the five observers used by Dr. Ives at the intensity of light which he calls most favorable to agreement for the two methods (250 Illumination Units). It will be seen that the disagreement for these observers is in the average as great, if not greater than was gotten by our own observers. Percentage of overestimation by the method of flicker is designated by +, and underestimation by -.

¹ Ives, H. E., *op. cit.*, p. 171.

² Luckiesh, M., *op. cit.*, p. 620.

³ Schenck, F., 'Ueber die Bestimmung der Helligkeit grauer und farbiger Pigmentpapiere mittels intermittierende Netzhautreizung,' *Pflüger's Archiv*, 1896, 64, pp. 607-628.

⁴ Dow, J. S., *op. cit.*, pp. 130-134; 'Physiological Principles Underlying the Flicker Photometer,' *Philos. Mag.*, 1910, 19, Ser. 6, pp. 58-77.

⁵ Ives, H. E., *op. cit.*, p. 172.

TABLE IX

Showing in percentage the difference in results between the methods of flicker and equality of brightness for the five observers used by Dr. Ives at the intensity of light which he calls most favorable.

λ	H. E. I.	M. L.	P. W. C.	C. F. L.	F. E. C.
.653 μ	-12. %	+29. %	-18. %	-51. %	-50. %
.643 μ	- 3.6	+56.	- 7.0	-31.	-23.7
.632 μ	- 4.3	+20.	-15.5	-45.5	-12.9
.622 μ	- 7.3	+12.5	- 4.2	-42.	-15.9
.612 μ	-10.	+ 8.3	- 6.5	- 7.5	+ 0.3
.594 μ	- 1.	- 0.5	- 0.5	+ 7.5	+ 5.8
.574 μ	+ 0.5	- 2.4	- 2.5	+27.	- 5.9
.555 μ	- 0.4	- 8.0	-11.9	- 4.8	+ 8.9
.545 μ	- 3.1	- 8.4	-13.8	+ 3.	+ 8.
.536 μ	- 1.9	- 4.0	-12.6	-12.	+14.3
.526 μ	0	- 8.7	-21.4	- 3.	+33.5
.517 μ	+ 0.6	-10.8	-13.8	-33.	+30.0

It has been our purpose in general in this part of the paper to indicate a field of investigation in the department of physiological optics about which little is known as yet with certainty, rather than to report a finished piece of work or to attempt to draw positive conclusions. When functioning under the conditions imposed by the method of flicker, too little is known of the characteristics of the eye, we believe, to render safe its use as a measuring instrument. Our purpose in particular has been to point out and show the effect of a factor which we believe to be an important source of disagreement between the equality of brightness and the flicker methods, and to suggest that a more careful study be made of the factors that influence the method of flicker before it is adopted in its present form as the method for the standardizing laboratories. Just as one factor has been overlooked, so there may be others the influence of which should not be ignored.

APPENDIX

Three other points which may be of interest in connection with the above work are appended here. The first two were discussed by Dr. Ives in a series of articles on the method of flicker in the *Philos. Mag.*, 1912, 24, Ser. 6, pp. 149-188, 352-370, 744-751, 845-853, 853-863. (1) In the third of his series of articles, he apparently wishes to show that the cause

of the disagreement between the results of the methods of flicker and equality of brightness lies on the side of the latter method. That is, the difficulty of making the judgment is so great that not an equalization, only an 'appraisement' is accomplished. To demonstrate this, he attempts to get rid of the disturbing factor of color difference in the equality of brightness method by making his comparisons always between lights differing only slightly in composition. That is, a green is compared with a green slightly shifted toward the yellow or blue, etc. (See his work with the 'cascade' method, p. 748.) A curve of luminosity for the spectrum obtained in this way is found to agree more closely with the flicker curve than one obtained in the ordinary way. The following things may be said of this demonstration, however. In the first place, he states that the cumulative errors are so great in the method that he could not begin at one point in the spectrum having a given luminosity and work in a given direction, then reverse this direction of working and obtain at all a close approximation to the luminosity value for the point at which he started. For this reason he drops the point by point procedure of the 'cascade' method, and plots his curve by taking his observations at twelve points in the spectrum. From the observations of these points the whole curve is constructed. In the second place, his method does not entirely accomplish his purpose of getting rid of all difference in color quality between the lights compared. In order to add some further data bearing upon the question whether the lack of agreement hitherto found between the results obtained by the equality of brightness and flicker methods could have been due to the difficulty of making the equality of brightness judgments of fields differing in color quality, we have thought it worth while to make the comparison using an equality of brightness method which for the purposes of this investigation presents, we believe, some points of advantage over the method used by Dr. Ives.¹ That is,

¹ We do not, however, mean to propose this as an entirely satisfactory method of heterochromatic photometry for the reason given in the discussion of the relation of the method to the Talbot-Plateau law (see footnote p. 149). We are using the method here merely to show that when the disturbing factor of color difference in the

the method we have used offers even less chances for errors in judgment, is simpler, and entirely eliminates the presence of a second color in the fields to be compared. The method is as follows: The sectorized disc was adjusted so that its outer edge bisected vertically the photometric field. A standard colorless light was moved to the position on the photometer bar that gave the judgment of equality by the method of flicker, and the disc was rotated at the fusion rate. Half of the field was thus of color of the original saturation and luminosity, and the other half was a fusion of the colored sector of the original saturation and luminosity and a gray sector of the luminosity of the color as determined by the method of flicker. Now, if the luminosity of the color by the method of flicker were the same as by the equality of brightness method, the two halves of the photometric field should match in luminosity (within the limits imposed by the Talbot-Plateau law).¹ That is, the addition of the colorless

fields to be compared is eliminated from the equality of brightness method, there is still a large, in fact an apparently undiminished characteristic difference between the results of the equality of brightness and flicker methods, which, so far as one can see, can in no way be ascribed to the equality of brightness method employed. The degree to which the influence of color difference on the judgment of the brightness equality of the fields compared is removed by this method is shown by the greatly increased reproducibility of the judgment. For our observers, the reproducibility is almost as great as it was for the method of flicker. There was thus but little more of the element of appraisalment in this method than there was in the method of flicker, while the characteristic difference in the results obtained by the two methods was not, so far as could be determined, appreciably lessened.

¹ A few words are needed to explain what is meant above by "within the limits imposed by the Talbot-Plateau law." It could scarcely be expected from a consideration of this law that the two fields would match especially under the dark-room conditions under which photometry is done, even when the gray sector was chosen equal in brightness to the color by the equality of brightness method. That is, when the colored is mixed with the gray sector by the method of successive impressions, there is a reduction of the intensity of each impression which is the same as would be gotten were the intensity of each light to be reduced in proportion to the time of exposure of the eye to each light to the total time of exposure of the eye to both lights. (See the discussion of the Talbot-Plateau law, p. 121.) That is, if the value of each sector is 180° , the impression made upon the eye by each light is the same, according to the Talbot-Plateau law, as if both lights were reduced one-half in intensity. But in suffering the reduction, the luminosity of the colored sector is not changed the same in amount as is that of the gray sector. If it is blue or green, for example, its brightness is not reduced so much as is that of the gray sector, and its fusion with the gray sector tends to lighten that sector and to make the second half of the field lighter than

to the colored sector would produce no change in its luminosity, and the two halves of the field would present a fully saturated color of a given luminosity and a less saturated color of the same luminosity (within the limits imposed above). But if there were an underestimation or an overestimation of the luminosity of the color by the method of flicker, the brightness of the second half of the field would be modified in this direction in proportion to the value of the colored and colorless sector; and if the underestimation or overestimation were great enough the two halves would not match. In proportion as the colorless sector is made larger in the second half of the field, the color of the mixture loses saturation, and the comparison with the fully saturated half of the fields becomes more difficult to make. On the other hand, in proportion as the colored sector is made larger, the effect on the brightness of the mixture of the difference between the flicker value and the true sensation value, if such a difference exists, is lost. After considerable preliminary investigation it was decided to use in turn colored sectors of the value of 300° , 270° , and 180° . The comparison was made for lights of the intensities specified in the preceding sections of the paper. In all cases when the color was red or yellow, the

the first. If, however, the colored sector is red or yellow, it is reduced more in brightness than is the gray sector, and its fusion with that sector tends to darken it and so to render the second half of the photometric field darker than the first. We have conducted experiments to determine whether the above effect, which is a direct corollary of the Talbot-Plateau law, actually takes place in observable amounts. When the light of the spectrum or light of the purity given by the Wratten and Wainwright filters was used, we found that it did. That is, when the second half of the field was green or blue and was fused with a gray of the luminosity of the color employed, determined by the equality of brightness method, this half of the field was observably lighter than the first half. Conversely, when red or yellow was used, the second half of the field was darker than the first. The effect, however, was not nearly so great as it was when the gray sector was made of the brightness of the color as determined by the method of flicker. That is, if two experiments are conducted, one in which the second half of the field is made by fusing the colored sector with a gray sector of the brightness of the color as determined by the equality of brightness method, and the other in which this half of the field is made by fusing the colored sector with a gray sector of the brightness of the color as determined by the method of flicker, the difference in brightness between the two halves of the field is quite appreciably greater in the second case than in the first. For example, when the colors are green and blue, the second half of the field is more too light in the second case than in the first; and when red and yellow, it is more too dark.

second half of the field was darker than the first; and when either blue or green, was lighter than the first half of the field. Determinations were made also of how much the colorless light had to be moved to make the two halves of the field match. These distances were not much different from those contained in the tables in the preceding sections of the paper expressing the difference in the estimation of the luminosity of the colors by the methods of flicker and equality of brightness (see pp. 136, 137),—certainly not any more than should be expected when it is remembered that a part of the effect of the difference is lost by mixing the colorless light representing the flicker determination with a sector of the colored light in its true luminosity value. The work was done also with pigment papers with a similar result. Thus it seems reasonable to conclude that the cause of the disagreement between the two methods can not be attributed entirely at least to the difficulty of making the equality of brightness judgment due to the difference in color quality between the fields compared, for in the above cases the color quality of the lights compared was the same. In the third place, disregarding the results of the above experiments, the writers scarcely need point out that it would be extremely difficult to explain such a systematic drift of luminosity in one direction in one part of the spectrum, and in the opposite direction in the other part, as we obtained, in terms of errors due to a false judgment of the sensations actually aroused. Moreover, it would be just as difficult to explain Dr. Ives's own reverse Purkinje effect in terms of a false judgment of the actual brightness values presented in sensation; or the closer agreement he obtains between the results by the methods of flicker and equality of brightness at high illuminations, in which case there is the maximum amount of color present and, therefore, the maximum color difference to disturb the equality of brightness judgment between colored and colorless light. Moreover, the kind of errors that one finds as due to uncertainty of judgment is a deviation on either side of a mean. This occurs when all other factors are eliminated if several judgments of the same sensation are made. Such

errors are compensated for by taking the average or mean of the determinations. If it is not conceded that they are compensated for, how, for example, can the average of the results by the equality of brightness method be taken as a standard in terms of which to evaluate the results obtained by other methods? (See Whitman, Schenck, Wilde, etc.).¹ Surely this should not be allowed if there were a consistent deviation in any one direction from the true brightness value for a given color due to errors in judgment. Moreover, such a characteristic drift due to errors in judgment is unknown in all previous work in psychophysics, and not only unknown, but unsuspected.

(2) In the fourth paper of the series,² Dr. Ives applies as a test to the method of flicker what he calls two axioms of measurement. These are (a) things which are equal to the same things shall be equal to each other; and (b) the whole shall be equal to the sum of its parts. He finds that the method of flicker satisfies these axioms better than the equality of brightness method. We would point out that these tests would not be expected to reveal to any considerable degree the influence of the factor we are discussing. They are tests which would apply as a check on the power to make the judgment of the brightness of the sensation properly, or to any tendency of this brightness equality to drift in one direction in any part of the spectrum without a compensating drift in the opposite direction in some other part of the spectrum; but they are not tests that could be expected to show whether or not there is underestimation in one half of the spectrum and overestimation in the other half. For example, the area of the curve of the spectrum plotted by the method of flicker might very well sum up to the value of the reassembled white light because of the compensating effect of the underestimation of one half of the spectrum and the overestimation of the other half.

(3) Since the foregoing paper was presented, the writers

¹ While Dr. Ives does not explicitly state that he takes the equality of brightness method as a standard in terms of which to evaluate the correctness of the results by other methods, the point of view is strongly implied in his first paper (*loc. cit.*).

² *Philos. Mag.*, 1912, 24, Ser. 6, pp. 845-853.

have met with the contention from a prominent advocate of the method of flicker that the effect of a reduction of intensity is not given by the method of flicker because each individual impression is carried over until the next is given, with sufficient intensity to preclude the effect of reduction. Whether or not each individual impression can be considered as carrying over with sufficient intensity to preclude the effect of reduction is an important point and should, lest the issue be in doubt, be included in a discussion of the principles underlying the method of flicker. It may not be out of place, therefore, for us to consider the question here briefly, even though it has not as yet, so far as we know, been discussed in print.

As evidence that each individual impression should be considered as carrying over with sufficient intensity to preclude the effect of reduction, it was contended, as the case was presented to us, that the rate used in the method of flicker is the fusion rate of the two impressions. Two reasons were given for considering this rate as the fusion rate. (1) If the two impressions be red and green, for example, yellow is produced at the rate of succession used in the flicker method. Yellow, it was pointed out, is a fusion of red and green, and, therefore, the rate used must be considered as the fusion rate for these colors. In answer to this point we would again call attention to the phenomena (see p. 116) which are produced in sensation when two impressions differing in color and brightness are given to the eye successively at different rates of speed.¹ When the rate is very slow, the effect of separate and distinct impressions is given, each in its proper color and brightness. When a little faster rate is used, the impressions become confused and a flickering effect is produced both in the color and brightness components of the sensation. When the rate is made still faster, the flickering of color dies out, leaving only brightness flicker; that is, the color components of the two sensations have been fused. That the brightness

¹ We wish at this point to state very emphatically that our account of the fusion of the color and brightness components of sensation at different rates of speed is not based on any theoretical conception of a separate brightness and color sense, but upon actual observation of the phenomena that take place when light impressions differing in color and luminosity are combined at different rates of succession. These phe-

components have not been fused, however, is attested by the presence of brightness flicker, which is now left outstanding in a field uniform as to color quality. As the rate of succession is made still faster, brightness flicker becomes less and less pronounced and finally disappears.¹ The rate at which this disappearance takes place is the fusion rate for the brightness components for the two sensations, and is much higher for all the colors than is the rate at which the fusion of the color components takes place.² (Interpreted in terms of the

nomena may be readily demonstrated by any kind of flicker photometer head if a sufficiently sensitive control of speed of rotation is had. (We have used for the control of speed of rotation a rheostat and motor especially constructed to give fine changes.) It can be very plainly and perhaps most conveniently demonstrated by rotating sectors of pigment papers at the proper gradations of speed in a good daylight illumination.

¹ We find that Krüss (*Physical. Zeitschr.*, 1904, 5, p. 67) gives a description of the phenomena that take place in sensation when two impressions differing in color and brightness are given to the eye successively at different rates of speed, very similar to that we have given here. He says: "If we slowly alternate the illumination from two differently colored light sources, for example, from a Hefner lamp and a gas burner, we clearly distinguish a succession of reddish and bluish bands with weak washed-out limits between them. As the rate of succession is increased it becomes progressively more difficult to distinguish the two colors from each other. At a comparatively low rate they begin to lose themselves in each other. At a slightly higher rate the difference in color disappears altogether and we have a color mixture. In this mixture, however, a brightness succession, a flicker, is observable which disappears only by a further increase in the rate of succession. Physiologically, it is of great interest that the distinguishing of separate colors ceases at a much slower rate of succession than the rate at which completely continuous sensation begins."

² The following values will serve to give a rough comparative showing of the rates at which the phenomena described above take place. The colors used were red and green. They were obtained from pigment papers of the Hering series of standard papers and from gelatine filters. Two intensities of color were employed in each case. The brightness of the Hering green for the lower intensity of illumination was .000814 cp. per sq. in.; of the red, .000594 cp. per sq. in. The phenomenon of separate impressions occurred from the lowest speed up to 6.9 revolutions per second. The impression of an intermingled color and brightness flicker was given from this rate up to 9.6 revolutions per second, at which rate the color components of the sensation fused, giving a field uniform as to color quality but with a strong outstanding brightness flicker. Brightness flicker was present until a speed of 22 revolutions per second was obtained. At this speed the brightness components in sensation were completely fused and the rotating disc presented a surface uniform both as to color and brightness. In making these determinations, the same sized field was used as was employed in our work with the method of flicker, *i. e.*, the disc was viewed through an aperture 3 mm. \times 3 mm. in a gray screen (Hering No. 24) 20 cm. from the eye. For the higher intensity the green surface was illuminated to a brightness of .00242 cp. per sq. in.; the

duration of the impression after the light has been cut off, this means, of course, that the brightness component in the sensation does not carry over under these conditions with as little loss of intensity as does the color component.) It is evident, then, that the rate of succession which is used in the method of flicker is at or near the fusion rate for the color components of the two sensations, not for the brightness components; nor is it anywhere near the fusion rate for the brightness components. But it is the brightness components in which we are interested in photometry. That is, it is in terms of the brightness component that all photometric judgments are made. The color components, when they differ in tone, only serve to confuse the judgment. It is, therefore, our object in all methods of photometry as much as possible to get rid of difference in the color components. This can be accomplished in the method of flicker only because of the fact we have just pointed out, namely, that the fusion of the color component in sensation comes at a much lower rate of succession than the fusion of the brightness component. That is, all color differences, whether sensed as distinct or as flickering sensations, disappear at a rate of succession that has little or no effect on eliminating the brightness factor, or in this case the equivalent of this elimination, the fusion of the brightness components of the two sensations. In fact, if there were no difference in the fusion rate of the color and brightness components, the flickering color impressions would so mask the presence of brightness flicker at any rate of succession that could be used, that the method would doubtless

red, .00167 cp. per sq. in. The phenomenon of separate impressions occurred from the lowest speed to 6 revolutions per second, at which rate color flicker began. Color fusion took place at 12.4 revolutions per second, and brightness fusion at 29.3 revolutions per second. At the lower intensity for the filters, the brightness of the green was .154 cp. per sq. in.; for the red, .099 cp. per sq. in. As compared with their brightness these colors were much more poorly saturated than were the Hering pigments. The phenomenon of separate impressions ceased and color flicker began at 6.5 per second. Color fusion took place at 11.5 revolutions per second, and brightness fusion took place at 35.4 revolutions per second. At the higher intensity for the filters the brightness of the green was .22 cp. per sq. in.; for the red, .143 cp. per sq. in. Color flicker began at 7 revolutions per second; color fusion took place at 12.9 revolutions per second; and brightness fusion was complete at 38.3 revolutions per second.

have little if any greater sensitivity than the equality of brightness method. (2) The second point that was cited in support of the contention that the rate used in the method of flicker is the fusion rate for the two sensations aroused, is that no brightness flicker is present when in terms of the method the two impressions are adjudged of the same brightness. This to the present writers seems indeed a strange confusion of meanings. Fusion is a term used to represent what takes place when two impressions or sensations differing in quality are combined into one, the same or homogeneous as to quality. This combination may be obtained in case of light stimuli, for example, by mixing two lights evenly and allowing them to act simultaneously on the eye; or it may be obtained by giving two lights to the eye in succession at such a rate that the sensation aroused by the one lasts over until the next one is set up with a sufficient degree of intensity to give the effect of continuity or homogeneity of quality. It may add to the clearness of our discussion, then, to consider what takes place in this regard when two impressions differing in brightness are given to the eye at the different rates of succession mentioned in the preceding paragraph. At the rate at which distinct and separate impressions are given, each sensation obviously dies away completely before the next one is aroused. If a rate slightly faster than this is selected, the sensation does not die away completely before the next one is set up.

There is a slight lasting-over from one impression to the next. This when the two impressions differ in brightness gives the effect of a wavering or flickering sensation. At the lowest speed at which flicker is produced, the effect of this lasting-over has its minimum value. As the speed is further increased it becomes greater and attains its maximum value at the rate of complete brightness fusion.¹ (See discussion of Talbot-Plateau law, pp. 121.) It is obvious, then, that the rate of speed employed in the method of flicker, which is, roughly speaking, the lowest rate at which brightness flicker

¹ At the fusion rate neither sensation rises to its maximum value, for example, nor has a chance to die away until the next one develops. The effect is that of a continuous sensation homogeneous as to color and brightness.

can be obtained unmixed with color flicker, is not the fusion rate for the brightness components in sensation nor is it anywhere near this rate.¹ It is equally obvious also that the absence of flicker when the final adjustment of the lights has been made for a photometric balance, can not be adduced as any evidence that this rate is the fusion rate for the brightness component of the two sensations, or, what is more significant in relation to the above mentioned claim, that it is a rate to which more than a minimum of lasting-over effect from impression to impression can be ascribed. Flicker is absent merely because, in accord with the purpose of the method, such an adjustment of the distance of the lights from the photometer head is made that the sensations aroused by the two lights are of equal brightness. Such sensations do not flicker whatever may be their rate of succession. It can, therefore, be considered as little more than absurd to adduce the absence of flicker when the photometric balance has been attained as evidence that the rate used is the fusion rate for the brightness components of sensation, and to pass from this to the conclusion that the same amount or anywhere near the same amount of carrying-over effect is present for this rate as obtains when the fusion rate is used. In fact, if this carrying-over effect were present to any considerable degree, the whole point of the flicker method would be lost. That is, it is the purpose in the method of flicker to select a rate of succession that will give the eye the maximum of sensitivity to brightness difference (or flicker), namely, the lowest rate at which flicker can be produced, rather than a rate that will fuse out this difference in sensation.

But supposing it could be established, as was contended, that we have in the rate used in the method of flicker a complete color and brightness fusion of the sensations aroused by the two lights, little would be gained for the claim that there is no reduction in the effect on sensation of the two lights employed, if it be granted, for example, that the Talbot-Plateau law is true. In substance this law is as

¹ Flicker and fusion are in fact antithetical terms, and the rates of succession which are favorable for each are widely separated in the scale of frequencies.

follows. When once the rate of rotation is sufficient to give a uniform sensation, the color and brightness of the disc are the same as they would be if all the light reflected from the sectors were evenly distributed over the surface of the disc; and no further increase in rapidity produces any effect on its appearance.¹ In terms of this law it is seen that the effect on

¹ See H. F. Talbot, 'Experiments on Light,' *Philos. Mag.*, 1834, Ser. 3, 5, pp. 321-334.

Talbot phrases this law as follows (pp. 328-329): "Since then these two things—the intensity of light and the time of the body's remaining in any given part of the circle—are each inversely proportional to the circumference of the circle it describes, it follows that they must be directly proportional to each other; that is to say, an irregular intermittent luminary whose observations are too frequent and too transitory for the eye to perceive, loses so much of its apparent brightness from this cause as is indicated by the proportion between the whole time of observation and the time during which it disappears." "The rapidity of the rotation does not affect the argument." To verify this reasoning, Talbot conducted experiments with reflected light using pigment surfaces and mirrors to send the light to the eye; and with transmitted light using sectored discs to cut down the time of exposure of the eye to various luminous sources.

In 1835 Plateau repeats and verifies Talbot's experiments. ('Betrachtungen über ein von Hrn. Talbot vorgeschlagenes photometrisches Princip,' *Poggend. Annal.*, 1835, 35, pp. 457-468). He concludes from his experiments as follows (pp. 462-463) "Nun muss zufolge des am Anfange dieses Aufsatzes dargelegten Principis die scheinbare Helligkeit der Scheibe sich zu der des Papiers verhalten wie die Vorübergangsdauer eines weissen und eines schwarzen Sectors; oder was dasselbe ist, wie die Winkelbreiten eines weissen Sectors zur Summe der Winkelbreiten eines weissen und schwarzen Sectors, oder endlich, was auch noch dasselbe ist, wie die Breite sämmtlicher weisser Sektoren zum ganzen Kreisumfang."

Swan, apparently working in ignorance of the writings of Talbot and Plateau, in substance formulates the law anew in 1849 (see W. Swan, 'On the Gradual Production of Luminous Impressions on the Eye and Other Phenomena of Vision,' *Trans. Roy. Soc. Edinb.*, 1849, 16, pp. 581-603. See also F. Boas, 'Ein Beweis des Talbot'schen Satzes und Bemerkungen zu einigen aus demselben gezogenen Folgerungen,' *Wiedem. Ann.*, 1882, 16, 359-362; A. M. Bloch, 'Expériences sur la vision,' *Compt. Rend. de la Soc. de Biol.*, 1885, 2, p. 495; A. Charpentier, 'Loi de Bloch relative aux lumières de courte durée,' *ibid.*, 1887 4, p. 5; etc.

For a more modern statement of this law and one also more consistent with the relation of changes in light energy to changes in sensation, see Helmholtz, 'Handbuch der physiol. Optik,' zw. Aufl., 1896, p. 483, "Wenn eine Stelle der Netzhaut von periodisch veränderlichem und regelmässig in derselben Weise wiederkehrendem Lichte getroffen wird, und die Dauer der Periode hinreichend kurz ist, so entsteht ein continuirlicher Eindruck, der dem gleich ist, welcher entstehen würde, wenn das während einer jeden Periode eintreffende Licht gleichmässig über die ganze Dauer der Periode vertheilt würde"; or E. C. Sanford, 'Experimental Psychology,' 1898, p. 146, "When once the rate of rotation is sufficient to give a uniform sensation, the color and brightness of any concentric ring are the same that they would be if all the light reflected

sensation is the same as is gotten by reducing the intensity of each light by an amount proportional to the ratio of the exposure time of that light to the total time of exposure to both lights; or in case the photometer head is a sectored disc, in proportion to the value of the given sector or set of sectors to 360° . That is, with a total value of each sector or set of sectors of 180° , the effect on sensation is the same as if each light were reduced one-half in intensity; if the total value of one sector or set of sectors is 90° , the effect on sensation is the same as if the light illuminating that sector were reduced to one-fourth of its intensity; if the total value were 45° , the same effect is produced as if the light were reduced to one-eighth of its intensity; etc. Thus, even if the rate of succession that is used in the method of flicker could be considered as the fusion rate for the brightness component of the sensation aroused, little advantage could be gained for the position in question. For the conclusion most certainly could not be avoided that the effect on sensation would be the same as if the lights were reduced in intensity, and by an amount proportional to the ratio of exposure time of each light to the total time of exposure to both lights.

The position under discussion seems also to involve to some extent a confusion of principle of the method of flicker with the method of critical frequency. For example, in the method of critical frequency, the impressions are given to the eye at the fusion rate. We need scarcely call to mind the procedure. One sector or set of sectors of the disc is illuminated by one of the lights to be compared and the other is black or of a very low luminosity. The disc is rotated at a rate which completely fuses the sectors in sensation. This light is then removed and the other light to be compared is substituted for it. The distance of this light from the disc is then adjusted until the rate of rotation required to produce fusion is the same as it was in the previous case. When this adjustment is obtained the intensity of illumination of the disc by the two lights is said to have been the same, and the from it were evenly distributed over its surface, and no further increase in rapidity produced any effect on its appearance."

relative brightnesses of the lights themselves are calculated by the law of inverse squares. The situation is, however, quite different for the method of flicker. Both sectors or sets of sectors of the disc are illuminated by the lights to be compared, and the rate of rotation is to be made such that if there were any brightness difference between the sectors, the maximum of flicker, not fusion, would be produced. If a rate were used that would produce fusion, for example, for any given amount of brightness difference, it is obvious that no difference in brightness equal to or less than this amount could be detected by the method. That is, the whole point of the method is to use a rate of speed that could not possibly be the fusion rate for any appreciable amount of brightness difference between the impressions to be compared; and in so far as this purpose can be realized in the different cases in which the method is employed, sensitivity for the method is obtained.

What our critic really needs to establish in order to support his position is that summation instead of fusion takes place. That is, if the total effect of each light on sensation is to rise to a higher level than is given by each individual impression, the individual impressions must in proportion to the rise summate or add their individual intensities. To produce this effect of summation, each individual impression would have to last over in sensation until the next impression of its kind is received, which, since the impressions alternate, could be the next impression but one. For example, when red and green lights are being compared, if the value of the red sensation is to rise to a higher level than that given by a single impression, the sensation aroused by one exposure to red would have to last over until sensation is aroused by the next exposure to red; that is, would have to last through the interval of exposure to green and into and wholly or partly through the succeeding interval of exposure to red. How highly improbable it is that this could happen to any degree that would be of saving consequence to the method, is shown by the following two considerations. (a) The wavering character of the sensation which we call flicker is due to the fact that a

given sensation does not carry over without a great loss of intensity through the next succeeding interval, let alone through the next interval but one. And (*b*) even at the rate at which complete color and brightness fusion takes place, there is according to the Talbot-Plateau law no effect of summation great enough to cause each individual sensation to attain to a higher intensity than that fixed by the ratio of the time of exposure of its stimulus light to the total time of exposure of both lights, nor to produce a noticeable change in this intensity, however great is the speed of the succession. That is, we have a reduction of the intensity of the sensation aroused by each light which is the same as would be gotten were the intensity of each light to be reduced by an amount proportional to the ratio of the time of exposure of that light to the total time of exposure of both lights, and no further increase in the rapidity of the succession produces any change in this effect.¹

With regard to the method of flicker, then, the case apparently stands as follows. The individual impressions are so short that the eye is very much underexposed to its stimulus, and the rate of succession is so slow that there is

¹ If one were permitted to interpret the Talbot-Plateau law with regard to what takes place when a rate of succession is employed greater than the fusion rate for both the colored and brightness components of sensation, two possibilities would be opened for explaining why no change in sensation is produced as the rate of succession is increased, and the length of each individual exposure is correspondingly decreased. (1) Either the increase in the reduction of the exposure-time causes no further reduction in the sensation aroused by the individual exposures; or (2) there is, owing to the increased rate of succession, a summation effect which just compensates for the reduction of the individual impressions. Now even if we were to accept as true the one of these alternatives which is the more favorable for the case of flicker, namely, that a compensating summation action takes place, and assume that this compensating summation obtains clear down to the rate of succession that is used in the method of flicker, we would have to expect as much reduction in the sensation aroused by each of the lights as is expressed by the Talbot-Plateau law. That is, the reduction for each would be the same as would be gotten were the intensity of each light to be reduced in proportion to the exposure-time of each to the exposure-time of both. As we have already pointed out, however, it is extremely improbable that there could be a compensating summation action at the flicker rate great enough to be of any considerable consequence to the method, because the wavering character of the sensation which we call flicker is due to the fact that a given sensation does not carry over without great loss until the next one develops, let alone until the next but one develops, which it would have to do to produce any summation effect.

not enough carrying-over from impression to impression to produce fusion, let alone the summation effect which is needed to cause the intensity of the sensation to rise to its full value or perhaps even to a higher level than would be given by a single exposure. Moreover, according to the Talbot-Plateau law a summation effect great enough to cause the sensation to rise to its full value is never produced, however fast is the rate of succession; for once the fusion rate is obtained, there is a reduction of the intensity of the sensation aroused by each light which is the same as would be gotten were the intensity of each light to be reduced in proportion to the time of exposure of that light to the total time of exposure to both lights, and there is no change in this effect however much the rate of succession is increased.

¹ Since the above discussion was presented to the Illuminating Engineering Society, Ives in collaboration with Kingsbury, has published a sixth article on the method of flicker (*Philos. Mag.*, Nov., 1914, 28 (167), pp. 708-728) in which a theory of flicker photometry is developed based on an analogy drawn between the response of the eye under successive stimulation to the action of incandescent lamp filaments under a fluctuating current. The gist of the article is that if the eye behaves under the conditions obtaining in flicker photometry as do lamp filaments (subject to certain modifications which are not in accordance with what is known of the functioning of the eye) under a fluctuating current, the method of flicker should give with high intensities of light at the photometer screen the same results on the average as the equality of brightness method. It is our purpose here merely to note the article, not to give a detailed discussion. The theory will be discussed in a later paper in connection with further experimental data. It may not be out of place to state at this time, however, that the analogy of the eye and the incandescent lamp filament is not based on experimental examination of the eye's manner of response, but is assumed. Moreover, considerable evidence is offered in the present paper, we think that the eye does not react to its stimulus given to it in succession at the flicker rate according to the laws which govern the temperature response of lamp filaments, more especially when the impressions differ widely as to wave-length. It has not been claimed, for example, that the flicker method does not give the same results as the equality of brightness method when the lights compared do not differ as to wave-length.

THE EFFICIENCY OF THE EYE UNDER DIFFERENT CONDITIONS OF LIGHTING: THE EFFECT OF VARYING THE DISTRIBUTION FACTORS AND INTENSITY.*

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Synopsis: In a previous paper** a plan of work was outlined by one of the writers for the study of the effect of different kinds of lighting conditions on the eye. The problem was divided into three parts: (1) the determination of the conditions that give in general the highest level or scale of visual efficiency; (2) the conditions that give the least loss of efficiency for continued work; and (3) the determination of the conditions that cause the least discomfort. Tests were described especially designed to meet the requirements of each of these divisions of the work and results were given to show in a general way the sensitivity of the tests employed. The work of the present paper is confined to the second division of the problem and should be considered as an explorative investigation for the determination of factors. Six aspects of lighting are considered provisionally as sustaining an important relation to the eye: the evenness of the illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity and quality. Only the first five of these are dealt with in this paper. The first four are called, for convenience of reference, distribution factors. In order to produce the variation in the distribution factors needed for the purposes of the test, three types of reflectors in common use were employed—a direct, a semi-indirect, and an indirect. These reflectors were selected with reference to the object of the investigation rather than as representative in every case of any particular principle of lighting. The illumination effects produced in each case were specified in the following ways: (1) A determination was made of the average illumination of the room under each of the three installations. (2) The brightness of prominent objects in the room, such as the test card, the reflectors for the semi-indirect installation, the reading page, specular reflection from surfaces, etc., was given. (3) Photographs were made of the room from three positions under each kind of installation. These effects were then correlated with the results obtained with the eye test.

In order to determine the effect of varying intensity with a certain grouping of distribution factors, lamps of different wattage were used with each type of reflector employed in the distribution series. The

*A brief report of the work described in this paper was read by one of the writers (Ferree) at the seventh annual convention of the Illuminating Engineering Society held at Pittsburgh, September 22-25, 1913.

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** TRANS. I. E. S., p. 49, vol. VIII (1913).

illumination effects produced were specified by illumination and brightness measurements in the way described above, and the effects were again correlated with the results of the eye tests conducted at each intensity of illumination.

I. INTRODUCTION.

In a paper¹ presented to the annual convention of this society last year, a plan of work was outlined by one of the writers for the study of the effect of different kinds of lighting conditions on the eye. The problem was divided into three parts: (1) the determination of the conditions that give in general the highest level or scale of visual efficiency, (2) the determination of the conditions that give the least loss of efficiency for continued work, and (3) the determination of the conditions that cause the least discomfort. Tests were described which seemed to the writer after six months of trial to be adequate for the requirements of each of these three divisions of work, and results were given to show in a general way the sensitivity of the tests employed. With the beginning of the present year work on the problem proper was begun. This work has been confined to the second division of the problem, namely, the determination of the conditions that give the least loss of efficiency as the result of a period of work. It has been thought best to conduct this investigation at first along broad lines in order to determine in a general way the conditions that affect the eye's ability to maintain its efficiency for continuous work. Later a more detailed examination will be made of the ways in which these conditions have been worked out in the various types of lighting systems in existence at this time.

The following aspects of lighting sustain an important relation to the eye: the evenness of the illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity, and quality. The first four of these aspects are very closely interrelated, and are apt to vary together in a concrete lighting situation, although not in a 1:1 ratio. For the purposes of this paper, therefore, which is the report of an investigation primarily explorative, it will be convenient to group these aspects together and refer to them as

¹ Ferrec, C. E., 'Tests for the Efficiency of the Eye under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort; TRANS. I. E. S., 1913, Vol. VIII, pp. 40-61.

the distribution of light and surface brightness in the field of vision, or still more generally as distribution. In later work an attempt will be made to study the effect of varying each in separation, but in the work here reported upon, no especial attempt has been made to do this. The ideal condition with regard to distribution is to have the field of vision uniformly illuminated with light well diffused and no extremes of surface brightness. When this condition is attained the illumination of the retina will shade off more or less gradually from center to periphery, which gradation is necessary for accurate and comfortable fixation and accommodation. Up to the present time, we have been able to finish in as complete a way as we wish for the installations used the work on distribution and part of the work on intensity. The remainder of the work will be completed early in the course of the present year.

The factors we have grouped under the heading distribution can most conveniently be discussed with reference to four types of lighting in common use to-day: illumination by daylight, illumination by direct lighting systems, by indirect lighting systems, and by semi-indirect systems. In the proper illumination of a room by daylight we have been able thus far to get the best conditions of distribution. Before it reaches our windows or skylights, daylight has been rendered widely diffuse by innumerable reflections, and the windows and skylights themselves acting as sources have a broad area and a low intrinsic brilliancy, all of which features contribute towards giving the ideal condition of distribution stated above, namely, that the field of vision shall be uniformly illuminated with light well diffused and that there shall be no extremes of surface brightness. Of the systems of artificial lighting, the best distribution effects from the standpoint of the comfort and efficiency of the eye are, speaking in general terms, given perhaps by the indirect systems. In this type of system the source is concealed from the eye and the light is thrown against the ceiling or some other diffusely reflecting surface in such a way that it suffers one or more reflections before it reaches the eye. The direct lighting systems are designed to send the light directly to the plane of work. There is in the use of these systems a tendency to concentrate the light on the plane of work or object viewed rather than to diffuse it, and, therefore, a ten-

dency to emphasize brightness extremes in the field of vision rather than to level them down. Too often, too, the eye is not properly shielded from the primary source of light, and frequently no attempt at all is made to do this. The semi-indirect systems are intended to represent a compromise between the direct and the indirect systems. A part of the light is transmitted directly to the plane of work through the translucent reflectors placed beneath, and a part is reflected to the ceiling. Thus, depending upon the density of the reflector, this type of system may vary between the totally direct and totally indirect as extremes and share in the relative merits and demerits of each in proportion to its place in the scale. It is not our purpose, however, at this time to attempt a final rating of the comparative merits of types of lighting systems. For that our work is still too young. Moreover, there are relatively good and bad fixtures of each type, and good and bad installations may be made of any system. What we hope to do is by the appropriate selection and variation of conditions to find out what the factors are that are of importance to the eye in lighting, and from this knowledge as a starting point to work towards reconstruction.

It was stated also in our former paper that the problem dealing with loss of efficiency presents two phases. We may investigate (*a*) whether the eye shows a loss of efficiency after three or four hours of work under a given lighting system, and (*b*) whether there is progressive loss of efficiency in working several months or years under a given system. We have confined and purpose to confine our work for the present to the former aspect of the problem, because it alone falls within the scope of laboratory studies and because we believe that the problem should be worked out first in miniature with all the conveniences of manipulation and possibilities of precision obtaining under laboratory conditions.

II. THE EFFECT OF VARIATION IN THE DISTRIBUTION OF LIGHT AND SURFACE BRIGHTNESS ON THE EFFICIENCY OF THE EYE FOR A PERIOD OF WORK.

In order better to understand the data given in the tables of results, the nature of the tests used in this part of the work will again be briefly called to mind. It will be remembered that the conventional tests for the eye's responsiveness to its stimulus,


namely, tests for brightness sensitivity, color sensitivity, and visual acuity, were found to be practically useless for this work. Modified and rendered sensitive in the ways described in the previous paper, they were found to serve as a measure of the general level of efficiency of the unfatigued eye under different conditions of lighting; but they failed to show loss of efficiency as the result of a period of work. This is due to the following reasons. (a) There is doubtless very little, if any, loss of sensitivity to brightness and color during this length of time.² It is commonly believed, in fact, that the brightness and color processes are compensating in nature. And (b) the visual acuity test, in spite of the fact that its results may be ascribed practically entirely to changes in the muscular control of the eye, is not adapted to show loss in muscular efficiency, because the muscles of the eye, while they may have fallen off enormously in efficiency, can under the spur of the will be whipped up to their normal power long enough to make the judgment required by the test. But they can not long sustain this extra effort. This consideration, it will be remembered, led us to continue the test through an interval of time. After considerable experimentation an interval of three minutes was chosen as best suited for our purpose. When the observer is required to look at the test card for three minutes, the test objects, even when the eyes are fresh, are not seen clearly for the whole time. They are seen alternately as clear and blurred. The time they are seen clear and blurred is recorded on a rotating drum upon which a line registering seconds is also run. From this record the ratio of time seen clear to time seen blurred is determined. This ratio may be fairly taken as a measure of the efficiency of the eye for three minutes of clear seeing at the time the test is taken. In applying the test to our problem, a record is taken at the beginning and at the close of work, and the ratios of the time clear and the time


² That there is practically no loss of sensitivity to brightness and color for this period of time was shown in our former paper by the results of our tests for brightness and color sensitivity with and without the time element as an aid to the test.

(See also in connection with tests for brightness and color sensitivity, Ferree and Rand: A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units, *Amer. Jour. of Psychol.*, 1912, Vol. XXIII, pp. 328-332; An Optics-Room and a Method of Standardizing its Illumination, *Psychol. Rev.*, 1912, Vol. XIX, pp. 364-373; Colored After-Image and Contrast Sensations from Stimuli in which no Color is Sensed, *ibid.*, pp. 195-239; Rand: The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing, *Psychol. Rev. Monog.*, 1913, 166 pp.; The Effect of Changes in the General Illumination of the Retina upon its Sensitivity to Color, *Psychol. Rev.*, 1912, Vol. XIX, pp. 463-490.

blurred are compared for the two cases to determine how much the eye has lost in efficiency as the result of work. Two values were used for the distance at which the test card was placed from the eye: (a) the maximal distance at which the test objects could be seen clearly in the momentary judgment, and (b) a distance less than this. The latter distance was finally chosen because for the maximal distance, towards the close of the test even when the eyes were fresh, the value of the time blurred became too high, it was found, to make the most effective comparison of the ratios obtaining at the beginning and at the close of work.

In order to eliminate the memory and fatigue factors which make it impossible to reproduce results in a series of tests with the same observer when the conventional Snellen test of visual acuity is employed, it will be remembered that the test card was made to consist of one or more simple objects, and the type of judgment was changed so that results were rendered in terms of clearness of vision instead of in terms of the ability to recognize a series of letters or characters.³ That is, in this type of test the observer knows what the objects are, and he records the time during which he sees them clear and the time he sees them blurred. A number of test objects were used in the work of last year: two vertical parallel lines stamped 1 mm. apart on a white

card; the letters li printed in small type, the figures ,

— • —, etc. To these was added this year the figure .

This form of test object was suggested by the one used in Dr. Ives' visual acuity apparatus.⁴ While apparently it gives ex-

³ For a further explanation of this point see Tests for the Efficiency of the Eye under Different Systems of Lighting and a Preliminary Study of the Causes of Discomfort, TRANS. I. E. S., Vol. VIII, 1913, pp. 43-45.

⁴ The writers wish to state that the test object used by them was similar to that employed by Dr. Ives only with regard to form. One of the prominent features of the apparatus used by Dr. Ives, for example, is a device for the control of the width of the parallel lines and the interspaces, while the figure used by us was printed on a white card with a fixed width of line and interspace. All that the writers wish to point out here is that a figure made up of parallel lines and interspaces is not, they believe, the most suitable for work of the kind we are doing because of the comparatively large mean variation it gives in the ratio, time clear to time blurred.

The figure was at first made 7 mm. in diameter; but this figure was found to be too large. It would blur irregularly over its surface, i. e., the edges would become indistinct when the center was clear and *vice versa*. The figure finally adopted was 3.5 mm. in diameter. This size was found to be more satisfactory for our work.

cellent results for the purpose for which it was adopted by Dr. Ives, it gives too large a mean variation of ratio, time clear to time blurred, when the element of time is introduced into the visual acuity test to be of maximal service in our work. This is probably because a figure of this form is more influenced by adaptation, the streaming phenomenon,⁵ and other variable physiological conditions of the retina than are, for example, the letters li. This latter object was found to be far the most satisfactory for our purpose. When used as test object the mean variation of the ratio, time clear to time blurred, for the same observer working under conditions as nearly constant as possible, is very small indeed.⁶ Results will be given, therefore, in this report only for the work in which the letters li were used as test object.

In our work on distribution the tests were made in a room 30.5 ft. (9.29 m.) long, 22.3 ft. (6.797 m.) wide, and 9.5 ft. (2.895 m.) high. The artificial lighting was accomplished by means of two rows of fixtures of four fixtures each. Each row was 6 ft. (1.828 m.) from the side wall, and the fixtures were 6 ft. apart. The reflectors were 29 in. from the ceiling for the direct system, and 16 in. for the indirect and semi-indirect. Clear tungsten lamps were used as source. The voltage was kept constant by means of a voltmeter and a finely graduated wall rheostat placed in series with the lighting circuit.

In order to get the desired variation in the distribution of light and surface brightness in the field of vision required for the purposes of the test, four types of lighting were selected. One may be called a direct system; one an indirect system; one a semi-indirect system; and one was the illumination of a room by daylight. In case of the direct system, two bulbs making an angle of 180 deg. were used for each fixture. Directly above the

⁵ Ferree, C. E., The Streaming Phenomenon, *Amer. Jour. of Psychol.*, 1908, 19, pp. 484-503; also The Intermittence of Minimal Visual Sensation, *Amer. Jour. of Psychol.*, 1908, Vol. XIX, pp. 112-130.

⁶ The order of magnitude of the mean variation of the test for the fresh eye was obtained as follows. Beginning at 9 A. M., five three-minute records were run with a rest period of 20 minutes between each test. This was done with all observers on several days under each system of lighting employed. The rest period was taken in each case in a room lighted by daylight facing a wall with an evenly lighted mat surface. For a single series of five tests, the variations of the time seen clear in the three-minute period have always fallen within 1 per cent. for all of the observers we have used and all systems of lighting.

lights was fastened a slightly concaved porcelain reflector 16 in. in diameter. This type of fixture was not chosen with an especial reference to its representative character in any system of commercial classification. It was chosen rather with reference to the purpose of the test. It may be said, however, that it was the one in use throughout the building in which the tests were made and gives effects very similar to much of the lighting in actual use at the present time. In case of the indirect system, corrugated mirror reflectors were used enclosed in a brass bowl. For the semi-indirect system inverted alba reflectors 11 in. in diameter were employed. The daylight illumination came from three windows all on one side of the room. These windows were so sheltered that it was never possible for them to receive light directly from the sun or from a brilliantly illuminated sky. Moreover, the light from one of them, the one nearest the observer, was further diffused by passing through a diffusion sash made of double thick glass ground on one side.

In order to get the effect of the distribution factors on the eye's loss of efficiency as the result of a period of work, the tests should be conducted with the quality and intensity of light made as nearly equal as possible. The quality of light was made approximately the same for the three installations of artificial light by using clear tungsten lamps in each case. It was decided to make the intensity of light as nearly equal as possible at the point of test, and to give a supplementary specification of the lighting effects in the remainder of the room for the three installations of artificial light.⁷ At the point of test the light was photometered in several directions. It was made approximately equal in the plane of the test card and as nearly as possible equal in the other directions.

The specification of the lighting effects in the remainder of the room has been accomplished as follows. (1) A determination

⁷ We have not as yet made the fuller photometric specification of the room lighted by daylight with our present arrangement of windows, curtains, etc. We hope to make the effect of varying the distribution factors in daylight illumination (employing windows, skylights, etc.) the study of a future study. In this study a photometric analysis of the illumination effects produced will be made an especial feature.

has been made of the average illumination of the room under each of the three installations. The room was laid out in 3-ft. squares, and illumination measurements were made at 66 of the intersections of the sides of these squares. Readings were made in a plane 122 cm. above the floor with the receiving test-plate of the illuminometer in the horizontal, 45 deg. and 90 deg. positions, measuring respectively the vertical, 45 deg., and horizontal components. The 122 cm. plane was chosen because that was the height of the test object. (2) A determination was made of the brightness of prominent objects in the room, such as the test card, the reflectors for the semi-indirect installation, book of the observer, specular reflection from surfaces, etc. The brightness measurements were made by means of a Sharp-Millar illuminometer with the receiving test plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal on a white card. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candlepower per sq. in. by the following formula: $\text{Brightness} = \text{Foot-candles} / \pi \times 144$. (3) Photographs were made of the room from three positions under each system of illumination.

In Fig. 1 (see "Further Experiments on the Efficiency of the Eye under Different Conditions of Lighting," *TRANS. of the Ill. Eng. Soc.*, 1915, X, p. 452a)⁸ the test room is drawn to scale: Plan of room, north, south, east, and west elevations.⁹ In the drawing plan of room, are shown the 66 stations at which the illumination measurements were made and the position of the outlets for the lighting fixtures A, B, C, D, E, F, G, H. In the drawing, east elevation, the position of the observer at one of the points at

⁸ The present paper is the second one in a series of three on the efficiency of the eye under different conditions of lighting. Before it was printed the third paper had been read at the eighth annual convention of the Illuminating Engineering Society and printed in the papers for that convention. In this paper it had been found necessary to repeat some of the data of the second paper for reference. Since both the second and third papers are now appearing simultaneously, the data that was repeated in the third paper has been omitted from the second. Wherever this has been done a cross reference is given to the third paper.

⁹ For the scale drawing of the test-room, for the measurements for the direct and semi-indirect systems given in Table II, and for the photographs of the test-room, we are indebted to Mr. C. W. Jordan of the United Gas Improvement Co.

which the tests were taken is represented.¹⁰ The other three positions are indicated by X.

Table I (see Table I, op. cit., p. 454) shows the number and wattage of the lamps used at outlets A, B, C, D, E, F, G, H; and Table II (see Table II, op. cit., 454-455) gives the illumination measurements for each of the 66 stations represented in Fig. 1, made with the receiving test plate of the photometer in the horizontal, vertical, and 45 deg. planes.

Table III has been compiled as a supplement to Table II for the purpose of making a comparative showing of the evenness of illumination at the 122 cm. level given by the three systems of lighting. Two cases may be made of this: (1) A comparison may be made of a given component from station to station; or (2) the difference between the components may be compared. To facilitate the comparisons, (a) the mean variation from the average of each of the components has been computed; and (b) the difference in the averages of the three components has been determined. Results for the first of these points are shown in Division A of the table; for the second in Division B.¹¹

¹⁰ The track along which the test card was moved was parallel to the east and west walls of the room. During the three hours of reading which intervened between the two tests the observer moved just far enough back from the upright supporting the mouthboard to give room for the book to be held and to permit of a comfortable reading position. The book was elevated and held approximately at an angle of 45 deg. When taking the test, the observer faced the north wall of the room, in such a position that with the eyes in the primary position, the lines of regard were parallel with the east and west walls of the room. Care was taken to have print of uniform size and distinctness for use with the three systems, and to have a page which gave a comparatively small amount of specular reflection. The brightness values of the page in the horizontal and 45 deg. positions for the three systems, are given in the legends for Figs. 8, 9, and 10.

¹¹ It would be interesting to make this comparison for other levels in the room and for a greater number of components. But unfortunately we have not been able to make the number of measurements needed for this comparison. The evenness of the illumination, it will be remembered, is not only of importance to the efficiency of the eye with reference to the object directly viewed, but also in its influence on the distribution of surface brightness. The evenness of surface brightness depends in general upon two sets of factors: (a) the nature and position of the reflecting surfaces in the room; and (b) the type of delivery of light to these surfaces.

We realize that the evenness of the illumination on the 122 cm. plane given by the indirect and semi-indirect units was somewhat interfered with by the reflectors of the direct system which were beneath and a little to the right of these units when in position for the test. Also the evenness of surface brightness on the ceiling for the direct system was interfered with by the indirect and semi-indirect reflectors, which were above and a little to the side of the direct units. The influence of this "dead apparatus" will be eliminated in the next series of installations. Moreover, the installation in each case was not such as to give the best effects obtainable from the type of reflector used. For example, the indirect reflectors were too close to the ceiling to give the maximum evenness of illumination and of surface brightness for the type of reflector used. The above analysis of effects is, therefore, not made for the purpose of drawing general conclusions with regard to the type of reflector employed. It is made solely for the sake of the comparison of the illuminating effects obtained with the corresponding results for loss of efficiency.

TABLE III.¹²—(DISTRIBUTION SERIES).

Compiled from Table II to show a comparison of the evenness of the illumination at the 122 cm. level given by the direct, semi-indirect, and indirect systems. Division A shows the mean variation from the average for each of the three components of illumination; Division B, the difference in the average value of the three components.

Division A.

System	Mean variation of the components			Percentage of mean variation of components		
	Vertical	Horizontal	45°	Vertical	Horizontal	45°
Direct	1.88	1.09	1.53	38%	47%	32%
Semi-indirect ..	1.68	0.66	1.32	39%	42%	36%
Indirect	1.1	0.4	0.61	30%	37%	19%

Division B.

System	Difference between components			Percentage of difference between components		
	Vertical and Horizontal	Vertical and 45°	45° and Horizontal	Vertical and Horizontal	Vertical and 45°	45° and Horizontal
Direct	2.68	0.23	2.45	54%	5%	51%
Semi-indirect ..	2.68	0.64	2.04	63%	15%	56%
Indirect	2.13	0.31	1.82	59%	9%	55%

¹² For Tables I and II, see Tables I and II, Further Experiments on the Efficiency of the Eye, etc., TRANS. I. E. S., 1915, Vol. X, pp. 454-455.

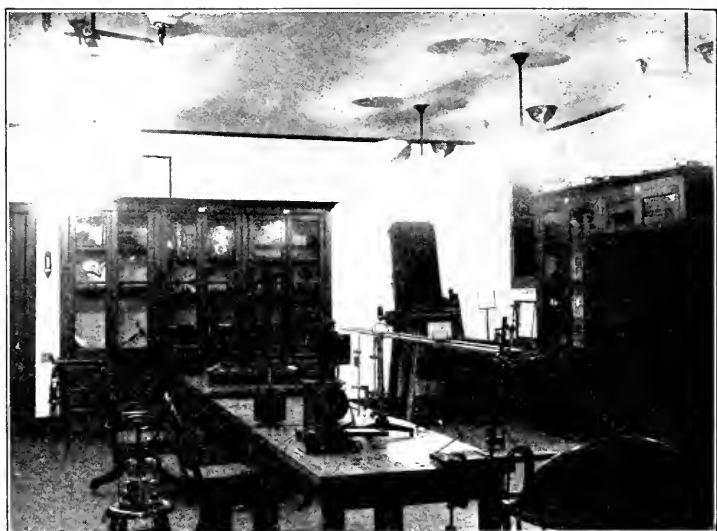


Fig. 2.—Showing the test room illuminated by the direct system. The photograph was taken from the south end of the room at a point 4 ft. from the west wall.

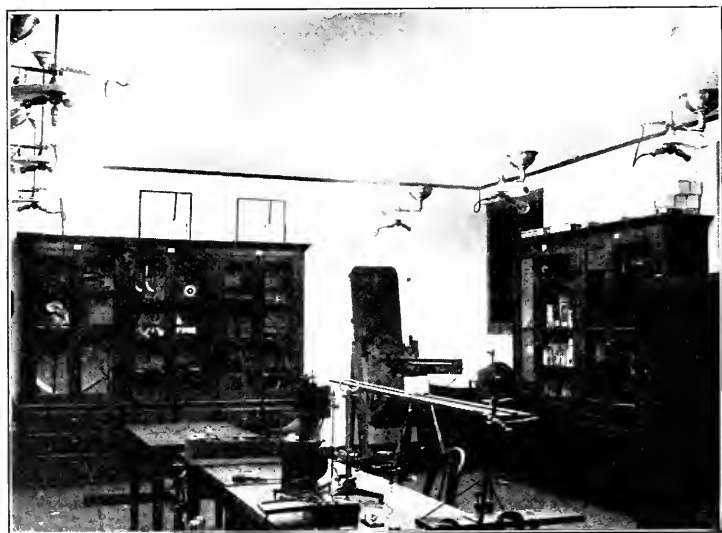


Fig. 3.—Showing the test room illuminated by the semi-indirect system. The photograph was taken from the south end of the room at a point 4 ft. from the west wall.



Fig. 4.—Showing the test room illuminated by the indirect system. The photograph was taken from the south end of the room at a point 4 ft. from the west wall.



Fig. 5.—Showing the illumination effects for the west wall of the room, direct system.



Fig. 6.—Showing the illumination for the west wall of the room, semi-indirect system.



Fig. 7.*—Showing the illumination effects for the west wall of the room, indirect system.

* For Figs. 8, 9, and 10, see Figs. 2, 3, and 4, "Further Experiments on the Efficiency of the Eye, etc." TRANS. of the I. E. S., 1915, Vol. X, pp. 452a-452b.

In Figs. 2 to 10 are given photographs showing the illumination of the room and the distribution of surface brightness for the three systems. Figs. 2, 3 and 4 are taken from the south end of the room at a point 4 ft. from the west wall. These photographs were taken so as to comprehend as much of the room as was possible in one view. They include the greater part of the ceiling, floor, and north wall; six of the fixtures; and about one-half of the east wall. The difference in surface brightness for the various points of the room (including the lighting units) is, it will be noted, greatest for the direct system, next greatest for the semi-indirect system, and least for the indirect system. The indirect and semi-indirect reflectors were attached to arms of approximately equal length which could be revolved about the fixture stem as an axis. When the tests were taken, these reflectors were turned in each case to the inside position indicated in the photograph, the object being to have the two types of reflectors as nearly as possible in the same position in the field of vision for the comparative tests. The direct fixtures, it will be noted, were below and slightly outside this position. In our next series of experiments, arrangements have been made such that the reflectors can be placed in exactly the same position for each type of installation when it suits the needs of the experiment to have it so. The slight deviation from exact coincidence found in these experiments is, however, perhaps of no great consequence for the purpose of the present work especially in the case of the indirect and semi-indirect reflectors. In Figs. 5, 6 and 7, are represented the illumination effects for the west half of the room. These photographs show the distribution of light and shade on the greater part of the west wall, and the adjacent ceiling, and include two of the fixtures. In Figs. 8, 9 and 10 (see Figs. 2-4, *op. cit.*, pp. 452a-452b) are shown the brightness measurements of all surfaces having very high or very low brilliancy. The spot measured is indicated by a cross, and the numerical value of the brightness measurement in candlepower per square inch is printed nearby. These spots are also lettered for convenience of reference in the intensity series. That is, since several installations were used in the intensity series it was found convenient to express these values in tabular form and to identify them with the surfaces measured

by means of letters. These photographs were taken from a point in the line with the four positions of the observer as near to the south wall of the room as was possible, but owing to the narrow field of the camera as compared with the binocular field, these views include, for example, only about one-half of the field of vision of the observer at the test station nearest to this end of the room. The camera's field in this position corresponds in fact very closely to the field presented to the observer seated at the center of the room. While, therefore, not all of his field of view for all the positions at which tests were made is covered by the brightness measurements shown in the photographs, still the order of magnitude of brightness differences present in the field of vision for the different systems is well represented by these measurements, as can be seen by an inspection of the preceding photographs and from the descriptions of the installations used.

In order to facilitate certain features of comparison such as, for example, of the evenness of surface brightness for each system for all of the room, for all but the sources or the sources and spots above the sources, the brightness measurements shown in Figs. 8, 9 and 10 are also given in tabular form. These measurements and the letters identifying them with the surfaces measured are given in Table IV and V. (see Table III and IV, *op. cit.*, p. 457). In making a comparison it should be noted that the spots measured are not in all cases identical for the three systems. That is, owing to the different effects produced by the different reflectors, the same spot was not always conspicuously light or dark for the three systems. The letters E, F, G, etc. may refer, then, to entirely different spots in case of the three systems.

In Tables VI and VII (see Table V and VI, *op. cit.*, pp. 463-464) are shown some prominent ratios of surface brightness for the three systems.¹³ In representing these ratios it has been consid-

¹³ In attempting to make comparisons of the effect of the different magnitudes of brightness ratios, one obviously must bear in mind that the surfaces between which the ratios are established are not in all cases in the same position in the field of vision for the three systems. For example, the brightest surfaces in case of the indirect system, namely, the spots on the ceiling directly above the reflectors are farther removed from the direct line of vision of the observer when in the working position than were the brightest surfaces in case of the direct and semi-indirect systems. The position of the surface in the field of vision would come into question, for example, in making a determination of the maximum value of brightness difference that the eye is adapted to stand. While we have done a great deal

(Continued on next page.)

ered important to make a comparative showing for the three systems (a) of the extremes of surface brightness; and (b) of the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work. The extremes of surface brightness are shown by giving the ratios between surfaces of the first, second, third, etc., order of brilliancy and the surface of the lowest order of brilliancy; and the comparison of the brilliancy of objects in the surrounding field to the brightness at the point of work by giving the ratios of the surfaces of the first, second, and third order of brilliancy to the brightness of the test card and the reading page in the working position. The following points may be noted. (1) The illumination effects produced by the direct system are characterized by great extremes of surface brightness and a high ratio of brilliancy of objects in the surrounding field to the surface brightness at the point of work. These effects are much less pronounced for the semi-indirect system, and still less for the indirect. (2) A comparison of this table with the tables showing loss of efficiency as the result of work shows that while the extremes of brightness are enormously larger for the direct than for the semi-indirect system, the eye loses almost as much in efficiency for three hours of work under the semi-indirect system as under the direct. That is, the greatest ratio of brightness for the direct system is over 1,000 times as much as the greatest ratio for the semi-indirect, while the difference in loss of efficiency for the two systems is comparatively insignificant. On the other hand the greatest ratio of brightness for the semi-indirect system is only about five times as much as for the indirect and the difference in loss of efficiency for three hours of work is very large, this loss of efficiency for three hours of work for the indirect system being, it will be noted,

of work on the effect of position of the brilliant surface in the field of vision in our investigation of the causes of discomfort, we have made no especial investigation of this point in relation to loss of efficiency. Doubtless what we shall all have to bear in mind is that even in the end we can not hope to specify narrowly what is most favorable, etc. in lighting conditions. The factors that enter into the concrete lighting situation are so complex, or rather are so variable and so rarely duplicated that we can hope to make general specifications with regard to what is most favorable, for example, only within very broad limits. If one wishes to work the conditions down to a finer point than this, the particular installation must itself be tested *in situ*. We are at present working on a shorter test which we hope will serve this purpose better than the test which has been used in the work described in this paper.

very small indeed. This seems to indicate (*a*) that for the scale of magnitudes present in this series of experiments, the gradation of surface brightness for the indirect system is very close to what the eye is prepared to stand without loss of efficiency; and (*b*) that an increase in differences in brightness above this point is followed at first by a rapid increase in loss of efficiency and later by a much slower increase. In the intensity series the following points also come out. (1) The effect of size of ratio on loss of efficiency is different for different orders of magnitude of brightness. That is, for the range of scale of magnitudes we have used, the lower is the order of magnitude, the greater is the ratio that is permissible. And (2) the size of the brilliant object as well as its brilliancy is of importance. That is, within certain limits, as yet undefined, an increase in the area of the brilliant surface causes an increase in loss of efficiency.

Supplementary to Tables IV-VII we have computed for the three systems the mean variation of the several brightness values from their average values. While important from the standpoint of showing the variation from the mean for the different systems, such a comparison is, however, probably not so important from the standpoint of the eye as are the comparisons given in Tables IV-VII. That is, from the standpoint of effect on the eye it is probably more important to give a representation of the brightness of individual surfaces, more especially of surfaces showing extremes of brightness, than it is the mean variation from the average brightness of all the surfaces. In order to make possible the comparison with and without the source and the spot above the source, the table is made to show separately the mean variation for the following measurements: (*a*) for all; (*b*) for all but the source; and (*c*) for all but the source and the spot above the source. Results are given in Table VIII.

Obviously the effect of these installations on the eye's ability to maintain its efficiency for a period of work will vary with the position of the observer in the room. The tests have been made, therefore, at four positions: one in which six fixtures were in the field of view, one in which four were in the field of view, one in which two were in the field of view, and one in which none were in the field of view. This variation of position at

which the observation was made accomplishes two purposes. (1) It gives us a more representative idea of the difference in the effect on the eye of the four types of lighting. And (2) it shows the effect of varying the number of surfaces showing brightness differences, particularly the number of primary sources in the field of view.

TABLE VIII.¹⁴—(DISTRIBUTION SERIES).

Compiled from Table IV to show the mean variations in surface brightness for the direct, semi-indirect, and indirect systems.¹⁵

Measurements considered	Mean variation for the three systems			Percentage of mean variation for the three systems		
	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect
All	94.977	0.075	0.0235	189%	145%	135%
All but the source	0.0018	0.01817	0.0235	33%	120%	135%
All but the source and the spot above the source	0.0016	0.0013	0.0012	32%	30%	35%

¹⁴ For Tables IV-VII, see Tables III-VI, Further Experiments on the Efficiency of the Eye, etc., TRANS. I. E. S., 1915, Vol. X, pp. 457, 463-464.

¹⁵ It is scarcely necessary to point out that the above results seem to indicate that the great advantage of the indirect over the other systems of lighting we have used with regard to the factor: evenness of surface brightness, comes primarily at least from its provision for shielding the eye from the light source rather than from any conspicuously greater evenness of illumination given by it to the objects in the field of view. In fact all of the systems give a fairly even distribution of surface brightness outside of the source and the surfaces immediately surrounding it.

The need of keeping the surface brightness within certain limits and the primary importance of properly shielding the eye from the source to the accomplishment of this desideratum are both obvious. Doubtless many ways will be devised in course of time for cutting down useless and harmful brightness differences in lighting effects. For example, the possibility is here suggested of producing a still smaller brightness difference than is given by the indirect reflectors of the type we have employed, by using semi-indirect reflectors of such a density as to give a surface brilliancy equal to that of the spot of light cast upon the ceiling. The value of this brilliancy, because of the larger area of luminous surface presented, could then be made smaller than that of the ceiling spot cast by the indirect reflector and still give the same amount of light to the room. A similar effect may be obtained with the indirect reflector by using lamps of lower wattage and adding the light needed to make up the deficiency by installing directly beneath the reflector lamps of low wattage in translucent enclosures of a density that will give a surface brilliancy equal to that of the ceiling spots. The effect of both of these devices would be to lower the surface brilliancy for a given light flux by increasing the area of the luminous surface. Whether either would be advisable from other standpoints we are not at present prepared to say.

Results will be given in this paper only for the position with six fixtures in the field of view. The results for the other positions will be given in a later paper. When working at the position with six fixtures in the field of view, our tests show that the eye loses practically nothing in efficiency as the result of three to four hours of work under daylight, it loses enormously for the same period of work under the direct installation, and almost as much under the semi-indirect installation. Under the indirect installation the eye loses a little more than under daylight, but not nearly so much as under the other installations.

The results of the work on distribution are given in Tables IX and X. Early in the work it was found that nearly as much difference in result was gotten for two as for three hours of work. In Table IX is shown the loss in efficiency for Observer R for three hours of work under the four systems; and in Table X, the loss in efficiency for Observer G for two hours of work. These tables are typical of the results obtained from all of our observers for these periods of work.¹⁶ Column 1 of these tables gives the type of lighting system. Column 2 gives the total wattage of the lamps used, and Column 3 the voltage at which these lamps were operated. Columns 4, 5, and 6 give the foot-candles of illumination at the point of work measured respectively in the horizontal, vertical, and 45 deg. planes. Column 7 gives the maximal distance at which the test object could be seen clearly, and Column 8 the distance chosen at which to conduct the test for loss of efficiency. Care was taken in every case to choose this working distance of such a value that the ratio it sustained to the maximum distance was always approximately the same. Column 9 gives the total time the test object was seen clear in the three minutes of observation and Column 10 the total time it was seen blurred. Column 11 gives the ratio of the total time seen clear to the total time seen blurred, and Column 12 gives the comparative values of these ratios in terms of a common standard. These ratios were reduced to a common scale or standard in order to make the comparison of the amounts of

¹⁶ Obviously in the consideration of the effect of a given lighting system on the ability of the eye to hold its efficiency for a period of work, the age of the observer and the condition of his eyes should be taken into account. For a full clinic report of the eyes of the observers employed, see *op. cit.*, foot-note 14, p. 460.

change in their ratios easier. They express the comparative ability of the eye to sustain its power of clear seeing for three minutes before and after work for the four conditions of lighting used.

It will also be noted from Column 8 of the above tables that the visual acuity tests show that acuity of vision as determined by the momentary judgment is higher for the same foot-candles of illumination under daylight than under artificial light, and of the artificial lights it is very slightly highest for the indirect system, next highest for the semi-indirect system, and slightly lowest for the direct. It will thus be seen that for all the purposes of clear seeing, whether the criterion be maximal acuity or the ability of the eye to hold its efficiency for a period of work, the best results are given in order by the systems that give the best distribution. The effect of distribution, however, on the ability of the fresh eye to see clearly, is not nearly so great as it is on its power to hold its efficiency for a period of work.

In order to give a typical representation in graphic form of the effect on the efficiency of the eye of a period of work under these four conditions of lighting, the results of the above tables will also be given in the form of a chart made up of straight lines showing in each case the loss of efficiency from beginning to close of work. In constructing these charts, the length of time of work is plotted along the abscissa, and the ratio of the time the test object is seen clear to the time it is seen blurred is plotted along the ordinate. Each one of the large squares along the abscissa represents one hour of work and along the ordinate an integer of the ratio. Chart A shows the results for Table IX, and Chart B for Table X. An inspection of these charts will show how widely different in amount is the loss in efficiency under the specified conditions for the direct and semi-indirect systems as compared with the indirect system and daylight, and how close is the correspondence between the results for the direct and semi-indirect system, and between the results for the indirect system and daylight.

The loss in efficiency found in the above work seems to be predominantly, if not entirely, muscular, for the tests for the sensitivity of the retina show practically no loss in sensitivity

TABLE IX.—(DISTRIBUTION SERIES).

Observer R, showing the eye's loss in efficiency as the result of 3 hours of work under the systems of indirect, semi-indirect, and direct lighting employed as compared with daylight. 8 lamps, indirect and semi-indirect systems; 16 lamps, direct system. Intensities equalized on test card. Clear tungsten lamps.

Lighting system	Watts	Volts	Foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear + total time blurred	Ratios reduced to common standard
			Hori- zon- tal	Verti- cal	45°							
Daylight	—	—	5.5	1.32	4.2	9 A.M. 12 M.	90.0	74.0	137	43	3.18	3.5
Indirect	800	107	5.2	1.36	3.5	9 A.M. 12 M.	90.0 84.5	74.0 67.5	135 135	45 45	3.0 3.0	3.3 3.5
Semi-indirect	760	107	5.8	1.45	4.0	9 A.M. 12 M.	84.5 80.5	67.5 68.5	132 142	48 38	2.75 3.73	3.2 3.5
Direct	880	107	4.2	1.41	2.6	9 A.M. 12 M.	79.5 81.0 78.0	68.5 68.0 68.0	92 139 71	88 41 109	1.04 3.39 0.65	0.97 3.5 0.67

TABLE X.—(DISTRIBUTION SERIES).

Observer G, showing the eye's loss in efficiency as the result of 2 hours of work under the systems of indirect, semi-indirect, and direct lighting employed as compared with daylight. 8 lamps, indirect, and semi-indirect systems; 16 lamps, direct system. Intensities equalized on the test card. Clear tungsten lamps.

Daylight	—	—	5.5	1.32	4.2	9 A.M. 11 A.M.	91.0	77.0	161	19	8.45	3.50
Indirect	800	107	5.2	1.36	3.5	9 A.M. 11 A.M.	91.0 85.0	77.0 72.0	160 159	20 21	8.00 7.57	3.31 3.50
Semi-indirect	760	107	5.8	1.45	4.0	9 A.M. 11 A.M.	85.0 83.0	72.0 72.0	157 159	23 21	6.83 7.55	3.15 3.50
Direct	880	107	4.2	1.41	2.6	9 A.M. 11 A.M.	81.0 78.0	72.0 69.5 69.5	150 145 131	30 35 49	5.00 4.14 2.67	2.30 3.50 2.20

Chart A (Observer R).—Showing the eye's loss in efficiency as the result of three hours of work under the systems of indirect, semi-indirect and direct lighting employed as compared with daylight.

Lighting system	Watts	Volts	Foot-candles		45°
			Horizontal	Vertical	
A—Daylight	—	—	5.5	1.32	4.2
B—Indirect	800	107	5.2	1.36	3.5
C—Semi-indirect . . .	760	107	5.8	1.45	4.0
D—Direct	880	107	4.2	1.41	2.6

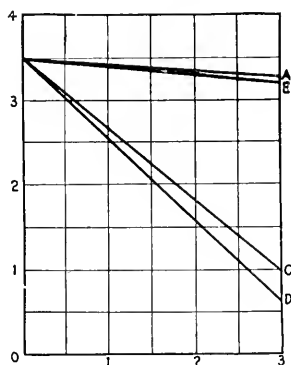


Chart A.

Chart B (Observer G).—Shows the eye's loss in efficiency as the result of two hours of work under the systems of indirect, semi-indirect and direct lighting employed as compared with daylight.

Lighting system	Watts	Volts	Foot-candles		45°
			Horizontal	Vertical	
A—Daylight	—	—	5.5	1.32	4.2
B—Indirect	800	107	5.2	1.36	3.5
C—Semi-indirect . . .	760	107	5.8	1.45	4.0
D—Direct	880	107	4.2	1.41	2.6

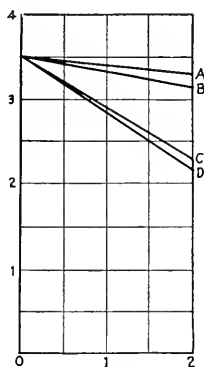


Chart B.

as the result of work under any of the installations employed.¹⁷ The following reasons are suggested why the muscles of the eye giving both fixation and accommodation should be subjected to a greater strain by the direct and semi-indirect installations than by the indirect installation or daylight. (1) The bright images of the sources falling on the peripheral retina, which is in a perpetual state of darkness-adaptation as compared with the central retina, and is, therefore, extremely sensitive in its reaction to such intensive stimuli, set up a reflex tendency for the eye to fixate them instead of, for example, the letters which the observer is required to read. (2) Likewise a strong reflex tendency to accommodate for these brilliant sources of light, all at different distances from each other and the lettered page, is set up. (3) These brilliant images, falling on a part of the retina that is not adapted to them, causing as they do acute discomfort in a very short period of time, doubtless induce spasmodic contractions of the muscles which both disturb the clearness of vision and greatly accentuate the fatiguing of the muscles. The net result of all these causes is excessive strain which shows itself in a loss of power to do work. In the illumination of a room by daylight, however, with a proper distribution of windows, the situation is quite different. The field of vision contains no bright sources of light to disturb fixation and accommodation and to cause spasmodic muscular disturbances due to the action of the intensive light sources on the dark-adapted and sensitive peripheral retina. As we have already pointed out, the light waves have suffered innumerable reflections and the light has become diffuse. The field of vision is, comparatively speaking, uniformly illuminated, and there are no extremes of surface brightness. The illumination of the retina, therefore, falls off more or less gradually from center to periphery, as it should to permit of fixation and accommodation for a given object with a minimum amount of strain.

¹⁷ In the next paper of the series it is shown (see op. cit. pp. 484-490) that the loss in muscular efficiency is confined largely to the accommodation muscles. The fixation muscles apparently suffer little loss for the period of work we have used.

III. THE EFFECT OF VARIATION IN THE INTENSITY OF LIGHT ON THE EFFICIENCY OF THE EYE FOR A PERIOD OF WORK.

It is not our purpose, however, to contend that distribution of light and surface brightness in the field of vision is the only factor of importance in the illumination of a room. The intensity and quality of light must also be taken into account. For example, one of the most persistent questions asked by the illuminating engineer is: "How much light should be used with a given lighting installation to give the best results for seeing?"

We have undertaken, therefore, to determine the most favorable range of intensity for the four types of lighting we have used. Our work shows in general the following results. A very wide range of intensity is permissible for daylight, and a comparatively wide range for the indirect installation. For the semi-indirect installation the eye fell off heavily in efficiency for all intensities with exception of a narrow range on either side of 2.2 foot-candles measured at the level of the eye at the point of work with the receiving surface of the photometer in the horizontal plane. For the direct installation no intensity could be found for which the eye did not lose a very great deal in efficiency as the result of work. Thus it seems that the factors we have grouped under the heading distribution are fundamental. That is, if the light is well distributed and diffuse, as it was in case of the daylight and indirect installations we used, and there are no extremes of surface brightness, the ability of the eye to hold its efficiency is, within limits, independent of intensity. In short, the retina is itself highly accommodative or adaptive to intensity, and if there is the proper distribution and diffuseness of light and the proper gradation of surface brightness in the field of vision, the conditions are not present which cause strain and consequent loss in efficiency in the adjustment of the eye. The results of this series of tests, then, accomplish two purposes. (1) They show that when the distribution and diffuseness of light and the distribution of surface brightness in the field of view are properly taken care of, the eye, so far as the problem of lighting is concerned, is practically independent of intensity. And (2) they show the effect on the efficiency of the eye of the variations in surface brightness pro-

duced by varying intensity in case of the direct and semi-indirect installations we have used.

The tests were made in the same room, with the same fixtures, and in general with the same conditions of installation and methods of working as were described in the work on distribution. To secure the various degrees of intensity needed, lamps of different wattage were used. These were selected from a series of tungsten lamps ranging from 15-100 watts. In order to keep the distribution factor as nearly constant as possible for a given type of system, the lamps used in making the test for that type of system were all of one wattage, *i. e.*, all 15's, 25's, 40's, 60's, or 100's.

For the semi-indirect system the total range of intensity of illumination employed is shown by the following figures. The series was begun with 25-watt lamps¹⁸ and consisted of 25, 40, 60, and 100-watt lamps.¹⁹ For the 25-watt lamps the photometer reading at the point of work with the receiving test plate of the photometer in the horizontal plane, showed 1.6 foot-candles; with the test plate in the vertical position 0.45 foot-candle; in the 45 deg. position 1.15 foot-candles. For the 100-watt lamps, 6.8 foot-candles were obtained with the test plate horizontal; 1.82 foot-candles with the test plate vertical; and 4.5 foot-candles with it in the 45 deg. position. The tests for loss in efficiency²⁰ showed that the intensity most favorable to the eye was secured

¹⁸ Since the most favorable intensity was given by the 40-watt lamps and since the 15-watt lamps gave so little light as to be extremely trying to the eyes, it was thought best to begin the series with the 25-watt lamps instead of the 15 as was done in case of the direct system.

¹⁹ Owing to their smaller size, socket extenders had to be used for the 25 and 40-watt lamps. That is, without the extenders these lamps came so low in the reflector as to change the distribution effects given by the reflector.

²⁰ In conducting these tests it was found necessary to allow a period of adaptation without work to the illumination of the room before the first test was taken. If this were not done, especially in case of the lower intensities of light used, the changing sensitivity of the eye to the intensity of light employed produced a noticeable change in the visual acuity between the times the tests before and after work were taken. Since the distance of the test card was kept the same for the two tests, this change in the visual acuity tended to influence the ratio: time clear to time blurred. To determine the length of time needed with a given intensity of light to insure a constant acuity so far as adaptation is concerned, preliminary tests were made as follows. The acuity of the observer was taken every three minutes until no noticeable change was found. This length of time was then always allowed for that observer as an adaptation period prior to the loss of efficiency test conducted for the intensity of illumination.

when the photometric reading with the test plate in the horizontal plane showed 2.2 foot-candles; in the vertical plane, 0.58 foot-candle; and in the 45 deg. plane, 1.52 foot-candles. The total wattage in this case was only 320. At this intensity of illumination the semi-indirect installation, so far as its effect on the eye is concerned, compares very favorably with the indirect installation at such ranges of intensity as we have employed. At intensities appreciable higher than this most favorable value, however, or appreciably lower, the loss in efficiency is very great. At the intensity commonly recommended in lighting practise, this semi-indirect installation is almost, if not quite as damaging as the direct installation. The intensity recommended by the Illuminating Engineering Society, for example, in its primer issued in 1912, ranges from 2-3 to 7-10 foot-candles, depending upon the kind of work; 5 foot-candles is taken as a medium value. This medium value is more than double the amount we have found to give the least loss in efficiency for the type and installation of semi-indirect lighting we have used. The intensity we have found to give the least loss in efficiency for this type of lighting does not, however, give maximal acuity of vision as determined by the momentary judgment. At an intensity that does give maximal acuity of vision as determined by the momentary judgment, the eye runs down rapidly in efficiency. That is, in this type of lighting one or the other of these features must be sacrificed. High acuity and little loss in efficiency can not both be had at the same intensity. These features can both be had only under daylight and, in case of the installations, we used, with the indirect system. However, the amount of light we find to give the least loss in efficiency seems to be sufficient for much of the work ordinarily done in the office or home. It is not enough, though, for drafting or other work requiring great clearness of detail. By giving better distribution effects this system is supposed also to be a concession to the welfare of the eye, but our tests show that this concession is not so great as it is supposed to be. In fact, installed at the intensity of illumination ordinarily used, or at an intensity great enough for all kinds of work, little advantage is gained for the eye in this type of lighting with reflectors of low or medium densities; for with these

intensities of light and densities of reflector, the brightness of the source has not been sufficiently reduced to give much relief to the suffering eye. Until this is done in home, office, and public lighting, we can not hope to get rid of eye strain with its complex train of mental and physical disturbances. If the semi-indirect principle of lighting is to be used with benefit to the eye, a density of reflector and type of installation must be employed that will give a gradation of brightness in the field of view in conformity with the limits of difference that the eye can stand without loss in efficiency or comfort.

In case of the direct system of lighting, we were able to improve the conditions so far as loss of efficiency of the eye is concerned, by reducing the intensity; but this system never proved to be so favorable in this regard as even the semi-indirect system. In the tests made under the direct system care was taken to have the fixtures as nearly as possible in the same position as they were for the semi-indirect system. Our fixtures for the direct system were so installed that either one or two lamps could be used in each fixture, totalling respectively 8 and 16. In order to get a wider range of intensity both numbers of lamps were used, *i. e.*, one series was made with 8 lamps and another with 16. Four intensities of light were used in each case. These intensities were secured in the 8-lamp system by using lamps totalling 120, 200, 320, and 480 watts. The foot-candles at the point of work ranged from 0.64 with the receiving test plate of the photometer in the horizontal, 0.32 in the vertical, and 0.49 in the 45 deg. position with the lamps totalling 120 watts, to 2.6 with the test plate in the horizontal, 1.02 in the vertical, and 2.0 in the 45 deg. position with the lamps totalling 480 watts. The four intensities were secured in the 16-lamp system by using lamps totalling 240, 365, 400, and 880 watts. The foot-candles at the point of work with the 16-lamp system ranged from 1.23 with the test plate in the horizontal, 0.54 in the vertical, and 0.935 in the 45 deg. position with the lamps totalling 240 watts, to 4.2 with the test plate in the horizontal, 1.41 in the vertical, and 2.6 in the 45 deg. position with the lamps totalling 880 watts. The most favorable intensity was secured by an installation that gave 1.16 foot-candles with the test plate in the horizontal, 0.45 in the

vertical, and 0.85 in the 45 deg. position. This intensity was given by the 8-lamp system with a total wattage of 200. At this intensity, however, the loss in the efficiency of the eye for three hours of work was almost four and one-half times as great as for the most favorable intensity for the semi-indirect system; and more than four and one-half times as great as for a wide range of intensities for either the indirect system or daylight.

The following specification was made of the illumination effects for the intensity series. (1) Illumination measurements were made for the highest intensity employed at the 66 stations in the test room. These measurements were made in the way described in the preceding section. For the other intensities employed, measurements were made at 9 representative stations to show in a general way the order of magnitude of reduction produced by using the lamps of lower wattages. (2) Brightness measurements were made of prominent objects in the room, such as the test card, the book of the observer, and all surfaces showing very high or very low brilliancy, for all intensities for all systems.

In Table XI are given the illumination measurements for the highest wattages used made with the receiving test plate of the photometer in the horizontal, vertical, and 45 deg. planes. Tables XII, XIII and XIV show the illumination measurements for the other wattages employed in the series at nine representative stations. These measurements are intended to show the order of magnitude of reduction of the illumination of the room produced by using the lamps of lower wattage. They conform in each case pretty closely, it will be noted, to the simple ratio of the wattages employed. Tables XV, XVI and XVII give the brightness measurements for these installations for the different intensities used. The points at which the measurements were taken are indicated by the letters A, B, C, D, E, F, etc., see Figs. 8 and 9. In Tables XVIII, XIX and XX are given the prominent brightness ratios for the different intensities used. It was stated in the preceding section that the order of magnitude of the brightness scale exerts an influence on the effect of brightness ratio on the eye's loss of efficiency. This influence is readily seen on comparing the results of Table XVIII with those of

Table XXI. That is, while the various brightness ratios remain pretty much the same for the different intensities of light employed, the least loss of efficiency was given by the 40-watt lamps. This loss was, for example, very much less than was given by the 100-watt lamps, not quite so much less than was given by the 60-watt lamps, and very little less than was given by the 25 watt lamps. The loss in efficiency for the 25-watt lamps can also doubtless be attributed in part to an insufficient amount of light. At least the testimony of the various observers was that not enough light was given by these lamps for ease and comfort in reading. The results of these experiments seem to show, then, that a given order of magnitude of brightness difference in the field of view has more effect on the efficiency of the eye when the general scale of brightness values is higher than when it is low.

A comparison of Tables XIX and XX with Tables XXII and XXIII shows the influence of the area of the bright surface on the ability of the eye to hold its efficiency for a period of work. For example, although it is shown in Table XIX that the ratios: lightest surface to darkest surface, and lightest surface to test card and reading page, are greater in the 16-lamp system for the 15 than for the 25-watt lamps, Table XXII shows that greater loss of efficiency is caused by the 25-watt lamps. Similarly, Table XX shows that in the 8-lamp system these ratios are greater for the 25 and 40 than for the 60-watt lamps, while Table XXIII shows that the 60-watt lamps cause the greater loss in efficiency. This may be explained as follows. The brightest surfaces in the field of vision for the direct system are the filaments of the lamps. The brightness measurements given in the table are in terms of candlepower per square inch. The candlepower per square inch is the same, for example, for the filaments of the 15 as for those of the 25-watt lamps. But since the darkest surfaces, the test card, and the reading page, are darker for the 15-watt than for the 25-watt system, the ratios: lightest to darkest surface, lightest surface to test card, and lightest surface to reading page, are greater for the 15 than for the 25-watt system. While, however, the candlepower per square inch is the same for the 15 as for the 25-watt filaments, the actual candle-

power is less for the 15-watt filaments because of their smaller area of surface. That is, the area of the brilliant surface or in terms of luminous effects, its actual candlepower must be taken into account in estimating the effect on the eye as well as the candlepower per square inch. The effect of area on sensation is well known in physiological optics (for example, see Abney, *Philos. TRANS.*, 1897, CXC, A, p. 169), and is expressed in the law that within limits an increase of area of the stimulus functions as an increase of intensity, although not in a simple ratio. Apparently, too, in its effect on the eye's power to maintain its efficiency for a period of work, an increase of area of the brilliant surface also functions within limits as an increase in intensity.²¹ Ratios expressed in candlepower per square inch do not seem therefore, in all cases to be an adequate specification of surface brightness, so far as its effect on the efficiency of the eye is concerned, unless the areas compared be the same.

²¹ The above explanation is, however, not complete. It shows only that the ratios: lightest to darkest surface, and lightest surface to test card and reading page, are greater for the 15 than for the 25-watt lamps because the candlepower per square inch not the actual candlepower was used in computing the ratios.

We are not at present able to give the ratio of actual candlepower of lightest to darkest, lightest to reading page, etc., because we did not measure the actual candlepower of the darkest surface, the reading page, etc., only the candlepower per square inch. However, since the test card and the reading page were of the same area in case of the different intensities, and the darkest surface of approximately the same area, ratios based on the total candlepower of the lightest surface (the lamp filament) and the candlepower per square inch of the darkest surface, test card, and reading page have comparative values. These ratios are very little different for the 15- and 25-watt lamps. That is, the ratio lightest to darkest for the 15-watt lamps = 28,698, for the 25-watt lamps = 28,933; lightest to test card for the 15-watt lamps = 11,828, for the 25-watt lamps = 12,616; lightest to reading page for the 15-watt lamps = 7,352; for the 25-watt lamps = 7,483.

A complete explanation of the result will doubtless involve two factors (1) the ratio of the actual candlepower of the lightest and darkest surfaces; and (2) the point brought out in connection with Tables XVIII and XXI, namely that a given order of magnitude of brightness difference in the field of view has more effect on the loss of efficiency of the eye when the general scale of brightness values is high than when it is low. From this we would expect, for example, that if the ratio lightest to darkest surface and lightest surface to test card and reading page were equal or approximately so for the 25- and 15-watt lamps, for example, the greater loss of efficiency should come with the lamps of higher wattage. Similarly for the 8-lamp system, the 60- and 40-watt lamps should cause a greater loss of efficiency than the 25-watt lamps. The 15-watt lamps with this system gave too little light to read with ease and comfort hence are ruled out of count in the comparison.

For investigating in detail the effect of area of the brilliant surface on the eye's loss of efficiency, the campimeter may prove of convenience and of service. This is one of the instances where the abstract may be used to advantage to supplement the concrete method of investigation. (See Memorandum on the Report of the Research Committee, *TRANS. I. E. S.*, 1914, Vol. IX, No. 4, p. 358.)

The great difficulty with the abstract type of investigation, as the writers see the case at this time, is that a determination of what is permissible with regard to one factor in isolation may not be at all permissible in conjunction with other factors. A more feasible plan seems to us to be to vary the factor over a certain practical range in an actual concrete situation. By a proper selection of the concrete situations employed the ground of all that is practicable in lighting can be covered, and the results obtained can have a safe application.

TABLE XI.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at each of the 66 stations represented in Fig. 1 for the highest wattage used in the intensity series for the semi-indirect system, and the direct system (16 lamps and 8 lamps).

Station	Horizontal			Vertical			45°		
	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts
1	1.74	1.17	0.75	—	—	—	—	—	—
2	1.86	1.10	0.63	—	—	—	—	—	—
3	1.80	1.33	0.76	—	—	—	—	—	—
4	1.66	0.91	0.76	—	—	—	—	—	—
5	2.68	1.50	1.40	—	—	—	—	—	—
6	4.00	1.90	1.25	—	—	—	—	—	—
7	4.40	2.10	1.20	—	—	—	—	—	—
8	3.80	3.30	1.90	—	—	—	—	—	—
9	2.85	2.20	1.25	—	—	—	—	—	—
10	1.86	1.12	0.70	—	—	—	—	—	—
11	1.88	1.42	0.90	—	—	—	—	—	—
12	2.90	2.80	2.60	0.55	0.45	0.44	1.00	1.70	1.42
13	5.50	5.00	3.40	0.67	0.49	0.41	2.85	3.00	1.75
14	6.80	2.60	1.70	0.74	0.49	0.45	3.40	1.50	0.98
15	6.80	2.25	1.73	0.74	0.50	0.41	3.40	1.18	0.92
16	6.80	4.40	4.00	0.69	0.41	0.41	3.60	2.40	2.40
17	3.50	2.60	2.40	0.67	0.41	0.45	1.74	1.48	1.80
18	2.00	1.10	1.10	0.60	0.47	0.48	1.11	0.63	0.67
19	2.95	1.39	1.40	1.14	0.67	0.70	1.94	1.00	1.12
20	2.40	2.40	2.50	1.13	0.80	0.92	3.80	1.60	1.75
21	7.00	3.80	3.00	1.60	1.18	1.20	4.30	2.40	2.24
22	6.70	2.40	1.90	1.48	0.83	0.66	4.10	1.54	1.28
23	6.60	3.00	2.00	1.50	1.01	0.75	4.35	2.10	1.30
24	6.40	5.00	2.90	1.62	1.67	1.00	4.20	3.35	2.00

TABLE XI.—(INTENSITY SERIES.)—(Continued).

Station	Horizontal			Vertical			45°		
	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts
25	4.20	2.80	2.30	1.40	1.15	0.82	2.50	2.00	1.45
26	2.23	1.46	1.10	—	—	—	—	—	—
27	2.45	1.42	1.20	—	—	—	—	—	—
28	3.95	2.80	2.20	1.54	1.22	0.83	3.10	2.30	1.82
29	6.80	5.80	4.10	1.82	1.48	1.00	4.30	4.20	2.82
30	6.70	3.20	1.70	1.78	1.11	0.75	5.10	2.50	1.40
31	7.40	2.85	2.10	2.20	1.06	0.81	5.20	2.35	1.60
32	7.10	5.15	4.00	2.10	1.18	1.20	5.20	3.80	2.90
33	4.10	3.50	2.40	1.75	1.05	0.98	3.20	2.70	2.05
34	4.60	2.65	2.35	1.76	1.35	1.41	3.40	2.20	2.10
35	6.80	4.00	3.10	2.40	2.00	1.44	5.20	3.30	2.50
36	6.40	3.60	2.00	2.45	1.61	1.00	4.70	2.50	1.68
37	6.20	3.20	1.70	2.48	1.64	0.95	4.75	2.70	1.42
38	7.00	4.30	3.20	2.52	2.15	1.50	5.40	3.50	2.40
39	4.40	3.00	2.70	1.95	1.50	1.44	3.68	2.60	2.20
40	2.37	1.26	1.10	—	—	—	—	—	—
41	1.70	1.43	0.95	—	—	—	—	—	—
42	3.30	2.70	2.40	2.00	1.42	1.15	3.30	2.40	2.25
43	7.00	4.90	3.60	2.38	1.87	1.17	5.62	4.10	3.00
44	7.10	3.70	2.00	2.88	1.48	1.00	5.78	2.65	2.00
45	6.80	3.60	2.05	2.65	1.51	1.15	5.60	2.35	2.10
46	7.10	4.70	4.00	2.58	1.45	1.20	5.40	3.70	2.95
47	3.65	2.50	2.45	1.82	1.24	1.17	3.20	2.20	2.20
48	3.70	2.60	2.50	1.92	1.45	1.50	3.50	2.15	1.80
49	6.20	3.60	3.00	2.45	2.10	1.60	5.00	3.10	2.18
50	6.00	2.50	2.00	2.70	1.80	1.24	5.20	2.55	1.85

TABLE XI.—(INTENSITY SERIES.)—(Continued).

Station	Horizontal			Vertical			45°		
	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts	Semi-indirect 800 watts	Direct (8 lamps) 480 watts	Direct (16 lamps) 400 watts
51	5.50	2.50	1.90	2.52	1.78	1.26	5.10	2.50	1.90
52	4.85	3.60	3.10	2.55	2.10	1.60	4.65	3.30	2.75
53	3.20	2.30	2.30	1.73	1.54	1.26	3.10	2.25	1.92
54	2.47	3.00	4.00	1.77	1.80	2.10	2.65	3.10	3.20
55	4.70	4.00	3.55	2.28	1.68	1.30	4.35	3.80	2.80
56	5.40	2.10	1.90	2.98	1.82	1.25	5.60	2.50	2.10
57	5.10	2.30	1.67	2.95	1.74	1.35	5.30	2.60	2.15
58	5.20	4.40	4.30	2.60	1.69	1.88	5.28	3.60	3.35
59	2.90	2.45	2.50	2.35	1.38	1.20	3.60	2.50	2.22
60	2.52	1.94	1.70	1.82	1.49	1.37	2.72	2.35	2.51
61	3.92	2.20	2.08	2.90	2.25	1.80	4.80	3.40	2.70
62	3.52	1.64	1.47	2.87	1.86	1.50	4.70	2.35	1.96
63	3.42	1.66	1.40	2.62	1.86	1.40	4.30	2.40	1.96
64	3.32	2.10	2.20	2.37	2.20	1.72	4.10	3.10	3.00
65	2.30	1.43	1.62	1.66	1.74	1.38	3.00	2.35	2.25
66	1.40	0.90	0.97	—	—	—	—	—	—
Average	4.44	2.72	2.14	1.93	1.48	1.12	4.03	2.55	2.06

TABLE XII.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the semi-indirect system.

Station	Horizontal				Vertical				45°			
	800 watts	480 watts	320 watts	200 watts	800 watts	480 watts	320 watts	200 watts	800 watts	480 watts	320 watts	200 watts
Card	6.8	3.3	2.2	1.6	1.82	0.94	0.58	0.45	4.5	2.4	1.52	1.15
12	2.9	1.79	1.0	0.75	0.55	0.35	0.22	0.17	1.49	0.76	0.51	0.4
16	6.8	3.2	2.0	1.32	0.69	0.44	0.23	0.15	3.6	1.75	1.03	0.68
31	7.4	3.6	2.2	1.6	2.2	0.94	0.58	0.44	5.2	2.4	1.53	1.15
34	4.6	2.1	1.45	0.95	1.76	0.9	0.58	0.43	3.4	1.68	1.12	0.74
39	4.4	1.79	1.17	0.93	1.95	0.86	0.54	0.41	3.68	1.52	0.95	0.73
45	6.8	3.3	2.2	1.4	2.65	1.3	0.82	0.58	5.6	2.7	1.7	1.19
54	2.47	1.31	0.87	0.7	1.77	1.15	0.62	0.48	2.65	1.47	0.95	0.76
58	5.2	2.82	1.9	1.44	2.6	1.35	0.87	0.63	5.28	2.68	1.8	1.3
Average .	4.44	2.66	1.78	1.11	1.93	1.16	0.77	0.48	4.03	2.42	1.61	1.01

TABLE XIII.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the direct system (16 lamps).

Station	Horizontal			Vertical			45°		
	400 watts	365 watts	240 watts	400 watts	365 watts	240 watts	400 watts	365 watts	240 watts
Card	1.86	2.1	1.23	0.8	0.6	0.54	1.46	1.33	0.935
12	2.6	1.45	1.43	0.44	0.275	0.265	1.42	0.68	0.85
16	4.0	4.4	2.6	0.47	0.34	0.385	2.4	2.4	1.55
31	2.1	2.1	1.45	0.81	0.735	0.575	1.6	1.68	1.1
34	2.35	2.3	1.84	1.41	1.49	1.08	2.1	2.5	1.57
39	2.7	2.6	1.5	1.44	1.55	0.825	2.2	2.4	1.19
45	2.2	1.75	1.45	1.27	1.3	0.77	2.1	1.95	1.23
54	4.0	1.6	1.34	2.1	1.13	0.78	3.2	1.64	1.38
58	4.3	2.3	2.5	1.88	1.25	1.02	3.35	2.1	2.1
Average	2.14	—	1.26	1.12	—	0.67	2.06	—	1.21

TABLE XIV.—(INTENSITY SERIES.)

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the direct system (8 lamps).

Station	Horizontal				Vertical				45°			
	480 watts	320 watts	200 watts	120 watts	480 watts	320 watts	200 watts	120 watts	480 watts	320 watts	200 watts	120 watts
Card	2.6	1.97	1.6	0.64	1.02	0.65	0.45	0.32	2.0	1.39	0.85	0.45
12	2.8	1.94	1.36	0.69	0.45	0.41	0.21	0.15	1.7	1.12	0.76	0.41
16	4.4	2.8	2.4	1.22	0.41	0.36	0.2	0.11	2.4	1.88	1.44	0.66
31	2.95	2.1	1.34	0.71	1.06	0.71	0.28	0.32	2.35	1.45	1.03	0.6
34	2.65	1.76	1.3	0.76	1.35	1.01	0.92	0.4	2.2	1.45	1.24	0.56
39	3.0	2.2	1.25	0.7	1.5	1.0	0.66	0.44	2.6	1.8	1.05	0.65
45	3.6	2.1	1.2	0.69	1.54	1.07	0.72	0.46	2.35	1.84	1.15	0.65
54	3.0	2.2	1.22	0.68	1.54	1.1	0.59	0.4	3.1	2.4	1.18	1.63
58	4.4	3.1	2.1	1.3	1.69	1.22	0.77	0.52	3.6	2.5	1.68	0.96
Average.	2.72	1.81	1.13	0.68	1.48	0.99	0.62	0.37	1.12	0.75	0.47	0.28

TABLE XV.—(INTENSITY SERIES.)

Showing the brightness measurements in candlepower per square inch for the different intensities used for the semi-indirect system at points indicated by the letters A, B, C, D, etc., see Fig. 3, Further Experiments on the Efficiency of the Eye, etc., TRANS. I. E. S. (1915), vol. X, p. 452b.

Position	800 watts	480 watts	320 watts	200 watts
A.....	0.687	0.370	0.180	0.1428
B.....	0.0461	0.0219	0.01402	0.01008
C.....	0.0858	0.0504	0.0346	0.02414
D.....	0.0461	0.0219	0.0163	0.01008
E.....	0.00264	0.00177	0.0008	0.00061
F.....	0.0034	0.00187	0.001034	0.000792
G.....	0.0058	0.00242	0.00187	0.00123
H.....	0.00662	0.00259	0.00162	0.00144
I.....	0.00638	0.00237	0.00187	0.00123
J.....	0.00149	0.00076	0.000484	0.000325
K.....	0.00462	0.00189	0.0014	0.000902
L.....	0.00255	0.00173	0.001085	0.00063
M.....	0.00572	0.00224	0.001408	0.0011
N.....	0.00286	0.00173	0.001085	0.00063
O.....	0.00704	0.00462	0.00264	0.00176
P.....	0.00616	0.003196	0.00198	0.00154
X.....	0.003432	0.00176	0.00105	0.000814
Reading page horizontal	0.0107	0.00462	0.0029	0.002024
Reading page 45° position	0.00654	0.00316	0.00193	0.00176

TABLE XVI.—(INTENSITY SERIES.)

Showing the brightness measurements in candlepower per square inch for the different intensities used for the direct system (16 lamps) at points indicated by the letters A, B, C, D, etc., see Fig. 2, Further Experiments on the Efficiency of the Eye, etc., TRANS. of the I. E. S., 1915, X, p. 452a.

Position	400 watts	365 watts	240 watts
A.....	1000.00000	1000.00000	1000.00000
B.....	0.1897	0.1232	0.1232
C.....	0.00253	0.00151	0.00151
D.....	0.00277	0.00145	0.00119
E.....	0.00097	0.00067	0.000545
F.....	0.00277	0.00185	0.00156
G.....	0.00303	0.00246	0.00172
H.....	0.00303	0.00229	0.00174
I.....	0.00316	0.00216	0.0018
J.....	0.00075	0.0004	0.000453
K.....	0.00252	0.00167	0.00176
L.....	0.00191	0.00149	0.00154
M.....	0.00273	0.00198	0.00194
N.....	0.00176	0.00145	0.00136
O.....	0.0026	0.00242	0.00143
P.....	0.00215	0.00167	0.00119
Q.....	0.00184	0.00103	0.00103
X.....	0.00172	0.00132	0.001
Reading page horizontal.....	0.00396	0.00405	0.00211
Reading page 45° position.....	0.0029	0.00273	0.00176

TABLE XVII.—(INTENSITY SERIES.)

Showing the brightness measurements in candlepower per square inch for the different intensities used for the direct system (8 lamps) at points indicated by the letters A, B, C, D, etc., see Fig. 2, Further Tests for the Efficiency of the Eye, etc., TRANS. of the I. E. S., 1915, X, p. 452a.

Position	480 watts	320 watts	200 watts	120 watts
A.....	1000.00000	1000.00000	1000.00000	1000.00000
B.....	0.2953	0.2398	0.1657	0.08998
C.....	0.00317	0.00299	0.00154	0.00097
D.....	0.00454	0.0033	0.00185	0.000704
E.....	0.001848	0.00118	0.00059	0.0003
F.....	0.00198	0.00272	0.00145	0.00063
G.....	0.00347	0.00361	0.00189	0.00074
H.....	0.00391	0.00334	0.00122	0.0011
I.....	0.00405	0.0029	0.00167	0.00092
J.....	0.00069	0.00046	0.00037	0.00023
K.....	0.00308	0.00167	0.00122	0.00073
L.....	0.00229	0.00141	0.00103	0.00056
M.....	0.00387	0.00229	0.00141	0.00068
N.....	0.00192	0.00128	0.00096	0.00054
O.....	0.00246	0.00252	0.00101	0.00065
P.....	0.00192	0.00185	0.00083	0.00051
Q.....	0.00325	0.00222	0.00136	0.000704
X.....	0.002376	0.00141	0.000924	0.00062
Reading page horizontal.....	0.00528	0.00334	0.00229	0.00123
Reading page 45° position.....	0.003696	0.0022	0.00149	0.00077

TABLE XVIII.—(INTENSITY SERIES.)

Showing some prominent ratios of surface brightness for the different intensities used for the semi-indirect system.

Ratio	800	480	320	200
Lightest to darkest.....	0.687 / 0.00149 = 455	0.37 / 0.00076 = 486	0.18 / 0.000484 = 372	0.1428 / 0.000325 = 439
Lightest to test card.....	0.687 / 0.00343 = 200	0.37 / 0.00176 = 210	0.18 / 0.00105 = 171	0.1428 / 0.000814 = 175
Lightest to reading page...	0.687 / 0.00654 = 105	0.37 / 0.00316 = 113	0.18 / 0.00193 = 93	0.1428 / 0.00176 = 81
2nd lightest to darkest....	0.0858 / 0.00149 = 57	0.0504 / 0.00076 = 66	0.0346 / 0.000484 = 71	0.02414 / 0.000325 = 74
2nd lightest to test card....	0.0858 / 0.00343 = 25	0.0504 / 0.00176 = 28	0.0346 / 0.00105 = 32	0.02414 / 0.000814 = 29
2nd lightest to reading page..	0.0858 / 0.00654 = 13	0.0504 / 0.00316 = 15	0.0346 / 0.00193 = 17	0.02414 / 0.00176 = 13
3rd lightest to darkest.....	0.0461 / 0.00149 = 31	0.0219 / 0.00076 = 29	0.0163 / 0.000484 = 34	0.01008 / 0.000325 = 31
3rd lightest to test card.....	0.0461 / 0.00343 = 13	0.0219 / 0.00176 = 12	0.0163 / 0.00105 = 15	0.01008 / 0.000814 = 12
3rd lightest to reading page..	0.0461 / 0.00654 = 7	0.0219 / 0.00316 = 6.9	0.0163 / 0.00193 = 8	0.01008 / 0.00176 = 6

TABLE XIX.—(INTENSITY SERIES.)

Showing some prominent ratios of surface brightness for the different intensities used for the direct system (16 lamps).

Ratios	400	365	240
Lightest to darkest.....	1000.00000 / 0.00075 = 1,333.333	1000.00000 / 0.0004 = 2,500.000	1000.00000 / 0.000453 = 2,207.505
Lightest to test card.....	1000.00000 / 0.00172 = 581.395	1000.00000 / 0.00132 = 757.575	1000.00000 / 0.0011 = 909.090
Lightest to reading page.....	1000.00000 / 0.0029 = 344.828	1000.00000 / 0.00273 = 366.300	1000.00000 / 0.00176 = 568.181
2nd lightest to darkest.....	0.1897 / 0.00075 = 253	0.1232 / 0.0004 = 308	0.1232 / 0.000453 = 272
2nd lightest to test card.....	0.1897 / 0.00172 = 110	0.1232 / 0.00132 = 93	0.1232 / 0.0011 = 112
2nd lightest to reading page.....	0.1897 / 0.0029 = 65	0.1232 / 0.00273 = 46	0.1232 / 0.00176 = 70
3rd lightest to darkest.....	0.00316 / 0.00075 = 4.2	0.00246 / 0.0004 = 6.15	0.0018 / 0.000453 = 4
3rd lightest to test card.....	0.00316 / 0.00172 = 1.8	0.00246 / 0.00132 = 1.8	0.0018 / 0.0011 = 1.6
3rd lightest to reading page.....	0.00316 / 0.0029 = 1.1	0.00246 / 0.00273 = 0.9	0.0018 / 0.00176 = 1.02

TABLE XX.—(INTENSITY SERIES.)

Showing some prominent ratios of surface brightness for the different intensities used for the direct system (8 lamps).

Ratio	480	320	200	120
Lighest to darkest.....	1000,00000/0.00069 = 1,449,275	1000,0000/0.00046 = 2,173,913	1000,00000/0.00037 = 2,702,702	1000,000000/0.00023 = 4,347,826
Lighest to test card.....	1000,00000/0.002376 = 420,168	1000,0000/0.00141 = 709,220	1000,00000/0.000924 = 1,086,960	1000,000000/0.00062 = 1,612,903
Lighest to reading page ...	1000,00000/0.003696 = 270,270	1000,0000/0.0022 = 454,545	1000,00000/0.00149 = 671,141	1000,000000/0.00077 = 1,298,701
2nd lightest to darkest	0.2953 /0.00069 = 428	0.2298/0.00046 = 519	0.1657 /0.00037 = 449	0.08995 /0.00023 = 390
2nd lightest to test card	0.2953 /0.002376 = 124	0.2298/0.00141 = 170	0.1657 /0.000924 = 179	0.08995 /0.00062 = 128
2nd lightest to reading page.	0.2953 /0.003696 = 80	0.2298/0.0022 = 109	0.1657 /0.00149 = 111	0.08995 /0.00077 = 117
3rd lightest to darkest	0.00454/0.00069 = 6.6	0.0033/0.00046 = 7.1	0.00185/0.00037 = 5.0	0.000704/0.00023 = 3.1
3rd lightest to test card	0.00454/0.002376 = 1.9	0.0033/0.00141 = 2.3	0.00185/0.000924 = 2.0	0.000704/0.00062 = 1.1
3rd lightest to reading page.	0.00454/0.003696 = 1.2	0.0033/0.0022 = 1.5	0.00185/0.00149 = 1.2	0.000704/0.00077 = 0.9

TABLE XXI.—(INTENSITY SERIES.)
Observer R, showing the effect on the efficiency of the eye of varying the intensity of light in the semi-indirect lighting system.

Watts	Volts	Foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear + total time blurred	Ratios reduced to common standard
		Hori- zon- tal	Verti- cal	45°							
320	107	2.2	0.58	1.52	9 A.M. 12 M.	73.5 71.5	58.5 58.5	117 112	63 68	1.86 1.65	3.5 3.1
320	110	2.31	0.62	1.61	9 A.M. 12 M.	74.0 72.0	57.0 57.0	140 135	40 45	3.5 3.0	3.5 3.0
200	110	1.72	0.484	1.29	9 A.M. 12 M.	72.5 72.5	57.5 57.5	138 130	42 50	3.27 2.6	3.5 2.78
200	107	1.6	0.45	1.15	9 A.M. 12 M.	65.5 65.5	51.5 51.5	141 123	39 57	3.61 2.14	3.5 2.07
480	107	3.3	0.94	2.4	9 A.M. 12 M.	79.0 76.5	63.5 63.5	124 96	56 180	2.21 1.11	3.5 1.75
800	107	6.8	1.82	4.5	9 A.M. 12 M.	85.5 82.5	66.5 66.5	126 62	54 118	2.33 0.525	3.5 0.78
760	107	5.8	1.45	4.0	9 A.M. 12 M.	80.5 79.5	68.5 68.5	142 92	38 88	3.73 1.04	3.5 0.97

TABLE XXII. — (INTENSITY SERIES.)

Observer R, showing the effect on the efficiency of the eye of varying the intensity of light in the direct lighting system. (16 lamps.)

Watts	Volts	Foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Ratios reduced to common standard
		Hori- zon- tal	Verti- cal	45°						
240	107	1.23	0.54	0.935	9 A.M. 12 M.	74.0 73.0	62.0 62.0	132 97	48 83	3.5 1.49
365	107	1.6	0.6	1.33	9 A.M. 12 M.	74.5 74.0	64.0 64.0	111 68	69 112	3.5 1.32
400	107	1.86	0.8	1.46	9 A.M. 12 M.	76.0 75.0	65.0 65.0	142 102	38 78	3.5 1.23
880	107	4.2	1.41	2.6	9 A.M. 12 M.	81.0 78.0	68.0 68.0	139 71	41 109	3.5 0.67

TABLE XXIII. — (INTENSITY SERIES.)

Observer R, showing the effect on the efficiency of the eye of varying the intensity of light in the direct lighting system. (8 lamps.)

Watts	Volts	Foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Ratios reduced to common standard
		Hori- zon- tal	Verti- cal	45°						
200	107	1.16	0.45	0.85	9 A.M. 12 M.	72.0 71.0	56.0 56.0	122 105	58 75	3.5 2.3
120	107	0.64	0.32	0.49	9 A.M. 12 M.	70.5 70.0	56.5 56.5	141 110	39 70	3.5 1.91
320	107	1.97	0.65	1.39	9 A.M. 12 M.	73.5 73.0	60.5 60.5	137 107	43 73	3.5 1.6
480	107	2.6	1.02	2.0	9 A.M. 12 M.	76.0 73.5	63.5 63.5	159 128	21 52	3.5 1.15

Showing the effect on the efficiency of the eye of varying the intensity of light in the semi-indirect lighting system.

	Watts	Volts	Foot-candles		45°
			Hori- zontal	Verti- cal	
A . . . 200	107	1.6	0.45	1.15	
B . . . 200	110	1.72	0.484	1.29	
C . . . 320	107	2.2	0.58	1.52	
D . . . 320	110	2.31	0.62	1.61	
E . . . 480	107	3.3	0.94	2.4	
F . . . 800	107	6.8	1.82	4.5	
X . . . 760	107	5.8	1.45	4.0	

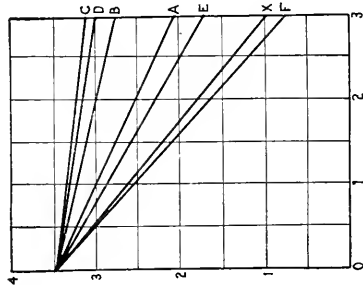


Chart C.

Showing the effect on the efficiency of the eye of varying the intensity of light in the direct lighting system. (16 lamps.)

	Watts	Volts	Foot-candles		45°
			Hori- zontal	Verti- cal	
A . . . 240	107	1.23	0.54	0.935	
B . . . 365	107	1.6	0.6	1.33	
C . . . 400	107	1.86	0.8	1.46	
X . . . 880	107	4.2	1.41	2.6	

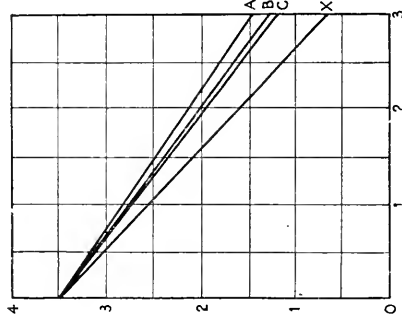


Chart D.

Showing the effect on the efficiency of the eye of varying the intensity of light in the direct lighting system. (8 lamps.)

	Watts	Volts	Foot-candles		45°
			Hori- zontal	Verti- cal	
A . . . 120	107	0.64	0.32	0.49	
B . . . 200	107	1.16	0.45	0.85	
C . . . 320	107	1.97	0.65	1.39	
D . . . 480	107	2.6	1.02	2.0	

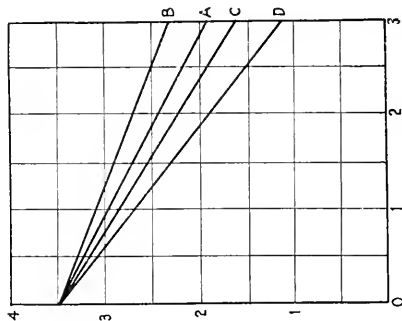


Chart E.

Chart F.—Showing the effect on the efficiency of the eye of varying the intensity of light for the semi-indirect system of lighting. Foot-candles at the point of the test card are plotted along the abscissa; loss of efficiency along the ordinate. X = points where the change in intensity was produced by changing the voltage (see Table XXI).

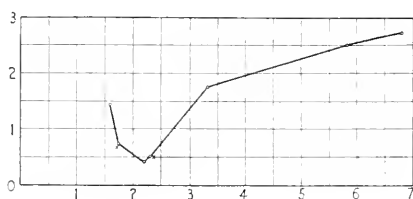


Chart F.

Chart G.—Showing the effect on the efficiency of the eye of varying the intensity of light for the direct system of lighting. Foot-candles at the point of the test card are plotted along the abscissa; and loss of efficiency along the ordinate. A = curve for 16 lamps; B, for 8 lamps.

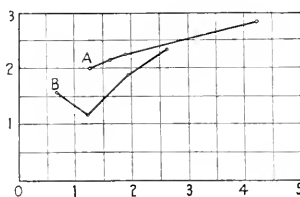


Chart G.

The results of the tests for the intensity series are shown in Tables XXI–XXIII. Three hours was selected as the period of work in all of these experiments. Briefly stated the procedure was as follows. First the most favorable intensity was determined and then variations were made on either side of this intensity until it was certain that the characteristic effect of increase and decrease of illumination was obtained. Table XXI gives the results for Observer R under the semi-indirect system. Seven variations of intensity were used. These results are typical of the effect of variations of intensities for this system. Tables XXII and XXIII show the results for the direct system for the same observer. For the direct system the most favorable intensity, it will be noted, was secured with the 8-lamp system with a total wattage lower than could be gotten with the 16-lamp system, *i. e.*, a system totalling 200 watts caused the least loss of efficiency to the eye, while 240 was the smallest total of wattage that could be secured with the 16-lamp system.

Charts have been constructed also to give a graphic representation of these tables. Chart C shows the results of Table XXI; Chart D, of Table XXII; and Chart E, of Table XXIII.

In these charts loss of efficiency was plotted against time of work. In Charts F and G loss of efficiency is plotted against intensity of light in foot-candles at the point of the test card. Chart F shows the results for Table XXI; Chart G for Tables XXII and XXIII.

IV. CONCLUSION.

Two facts may be emphasized at this point. (1) Of the lighting factors that influence the welfare of the eye, those we have grouped under the heading distribution are apparently fundamental. They seem to be the most important we have yet to deal with in our search for the conditions that give us the minimum loss of efficiency and the maximum comfort in seeing. If, for example, the light is well distributed in the field of vision and there are no extremes of surface brightness, our tests seem to indicate that the eye, so far as the problem of lighting is concerned, is practically independent of intensity. That is, when the proper distribution effects are obtained, intensities high enough to give maximum discrimination of detail may be employed

without causing appreciable damage or discomfort to the eye. (2) For the kind of distribution effects given by reflectors of the type employed in our direct and semi-indirect installations, our results show that unquestionably too much light is being used for the welfare of the eye.

Before concluding our paper we wish again to state that the units we have employed were not selected as fully representative of the classes direct, semi-indirect, and indirect. Agreement in fact has not yet been reached with regard to what falls within each of these classes. The units employed were chosen rather to show the effect on the ability of the eye to maintain its efficiency for a period of work of varying the factors we have grouped under the heading distribution. We hope ultimately to determine the limits between which each of these factors may vary without damage to the eye in a selected range of lighting situations, especially the factor surface brightness. These most favorable conditions will then serve as a goal to be attained whatever principle of lighting is employed.

Our next step in this division of the work will be to determine the effect on loss in efficiency of using reflectors of different degrees of opacity when the light is distributed to the plane of work both by the direct and indirect principles of lighting. That is, reflectors of different densities: prismatic, alba, opalux, totally opaque, etc., will be used turned up and down. In each case the installation will be made with special reference to giving the best results obtainable for the particular type of unit employed; and the factors: evenness of illumination, diffuseness of light, the angle at which the light falls on the work, and the evenness of surface brightness will be varied separately in turn, and the effect on loss of efficiency will be determined. Moreover, if it is found that the factors in question can not be studied in sufficient detail in the concrete lighting situation, the work will be supplemented by more abstract investigations. The results of this series of tests should give us among other things, for example, a still better idea of what amount of brightness difference the eye is adapted to stand, and the comparative effect of different ratios of surface brightness on loss of efficiency.





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FURTHER EXPERIMENTS ON THE EFFICIENCY OF THE EYE UNDER DIFFERENT CONDITIONS OF LIGHTING.*

BY C. E. FERREE AND G. RAND.

Synopsis: This paper is a continuation of the papers presented to the Society in 1912 and 1913. It describes the completion of the plan of work outlined in the preceding papers for one set of lighting conditions for three of the tests thus far devised by one of the writers (Ferree)—namely, a test of the ability of the eye to hold its efficiency for a period of work; a test for loss of efficiency of the fixation muscles; and a test for the comparative tendency of different conditions of lighting to produce discomfort. A report is also given of some miscellaneous experiments related to the hygienic employment of the eye in which the following points are taken up: the effect of varying the area and conversely the intrinsic brightness of the ceiling spots above the reflectors of an indirect system of lighting; the effect of varying the angle at which the light falls on the work in a given lighting situation; the effect of using an opaque eye shade with dark and light linings with each of the installations of artificial lighting employed in this and the previous work; the effect on the efficiency of the fixation muscles of three hours of work under these installations; the effect of motion pictures on the eye for different distances of the observer from the projection screen; a determination of the tendency of different conditions of lighting to produce discomfort, and a comparison of the tendency of these conditions to produce discomfort and to cause loss of efficiency.

INTRODUCTION.

The present paper is the third in a series of papers presented to this Society on the subject of lighting in its relation to the eye. In the first paper of this series¹ it was pointed out that if we are to make a comparative study of the effect of different conditions of lighting on the eye, we must have a means of estimating effects. Work was described in this paper in which

* A paper read at the eighth annual convention of the Illuminating Engineering Society, Cleveland, O., September 21-24, 1914.

The Illuminating Engineering Society is not responsible for the statements or opinions advanced by contributors.

¹ Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort, TRANS. I. E. S., vol. VIII, 1913, pp. 40-60.

the tests already known to physiological optics had been applied to the problem with negative results. New tests were proposed and brief results were given to show their feasibility for the problem in hand and to some extent their sensitivity. The suggestion was made that a systematic investigation of the effect of different conditions of lighting on the eye should include a study of the following points: (1) the efficiency of the fresh eye, (2) the loss of efficiency as the result of a period of work, and (3) the tendency to produce discomfort. In the second paper of the series,² presented to the Society last year, a plan of work was outlined and in part carried out in which the first two of the above points were covered for a given set of lighting conditions. The following factors of importance to the eye were enumerated: the evenness of illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity and quality. The first four of these factors are very closely interrelated and are apt to vary together in a concrete lighting situation, although not in a 1 : 1 ratio. It was convenient, therefore, for the purpose of this first investigation, which was primarily explorative in character, to group them together under one heading and to refer to them as distribution factors. In order to investigate the effect of certain wide variations in these factors, tests were conducted under four types of lighting in common use: one was the lighting of a room by daylight from windows; the others were the lighting of the same room by units commonly called direct, semi-indirect, and indirect, selected to serve the purposes of the test.³

² "The Efficiency of the Eye Under Different Conditions of Lighting—The Effect of Varying the Distribution Factors and Intensity." *TRANS. of the Ill. Eng. Soc.*, 1915, vol. X, pp. 407-447.

³ According to the plan as the investigation proceeds, the effect of varying each of these factors separately will be studied. No especial attempt was made to do this in the previous study. In making the experimental variations necessary to the investigation, it was stated as our purpose to keep as close as possible to actual lighting situations. More abstract investigations will be resorted to only when it becomes necessary to supplement the results by details that cannot be gotten from the concrete investigation. The objection to the abstract type of investigation, as the writers see the case at the present time, is that its results are very apt to be misleading. That is, what is permissible with regard to one factor in isolation, may not be at all permissible in conjunction with other factors. A more feasible plan seems to us to be to vary the factor over a certain practical range in actual concrete situations. By a proper selection of the proper situations employed, the ground of all that is practicable in lighting may be covered, and the results obtained can have a safe application.

For the systems of artificial lighting the tests were made at four positions in the room; one at which six of the eight lighting units employed were in the field of view, one at which four were in the field of view, one at which two were in the field of view, and one at which none was in the field of view. This variation of position at which the observation was made accomplishes, it was pointed out, two purposes. (1) It gives a more representative idea of the difference in the effect on the eye of the four types of lighting employed. And (2) it shows the effect of varying the number of surfaces in the field of view presenting brightness differences, more particularly the number of primary sources. The effect of varying intensity under each of the above conditions of distribution was also tested. The two sets of experiments were called respectively the distribution and intensity series. Results were given in the preceding paper for only one of the above positions in the distribution series, and for only the direct and semi-indirect systems for the intensity series. The results of the remainder of these two series of experiments, together with the report of some miscellaneous experiments will constitute the subject matter of the present paper. In these miscellaneous experiments, the following points have been taken up: the effect of varying the area and conversely the intrinsic brightness of the ceiling spots above the reflectors for the indirect system; the effect of varying the angle at which the light falls on the work; the effect of using an eye shade with dark and light linings with each of the three installations of artificial lighting; the effect on the efficiency of the fixation muscles of the eye of three hours of work under each of the conditions of lighting described in the distribution and intensity series; the effect of motion pictures on the eye for different distances of the observer from the projection screen; a determination of the tendency of each of the conditions of lighting that have been used in these experiments to produce discomfort, and a comparison of the tendency to produce discomfort and to cause loss of efficiency. Besides including some additional matter, these experiments, in connection with those of the preceding paper, complete the plan of work we had outlined for one set of lighting conditions for three of the tests we have thus far devised, namely, a test

for the ability of the eye to hold its efficiency for clear seeing for a period of work, a test for loss of efficiency of the fixation muscles, and a test for the comparative tendency of the different conditions of lighting to produce discomfort, with the exception that in a further analysis of the loss of efficiency caused by these lighting conditions, which will be carried out in part by means of these tests, data will be added later to show still more clearly the relative amounts of loss that are sustained by the different functions of the visual apparatus.

DISTRIBUTION SERIES.

As was pointed out in the former paper, in order to get the effect of variation in the distribution factors on the eye's loss of efficiency as the result of a period of work, the test should be conducted with the quality and intensity of light made as nearly equal as possible. The quality of light was made approximately the same for the three installations of artificial lighting employed by using clear tungsten lamps in each case. It was decided to make the intensity of light as nearly equal⁴ as possible at the point of test, and to give a supplementary specification of the lighting effects in the remainder of the room for the three installations of artificial light.

At the point of test the light was photometered⁵ in several directions. It was made approximately equal in the plane of the test card and as nearly as possible equal in the other directions. The specification of the lighting effects in the remainder of the room was accomplished as follows: (1) A determination was made of the average illumination of the room under each of the three installations. The room was laid out in 3-ft. (0.9 m.)

⁴ This equalization was made at the point of test for the position of the observer with six of the fixtures in the field of view. For the other positions illumination measurements were made in several directions at the test card, and brightness measurements were made of the surface of the test card and of the observer's book held in the horizontal and 45 deg. positions. Equalization could not have been made at all of these points without having changed the relation and magnitude of the distribution factors, which would not have been in accord with the purpose of the test, namely, to determine the effect of a certain grouping or relation of these factors for the four positions in the room.

⁵ We have not as yet made the fuller photometric specifications of the room lighted by daylight with our present arrangement of windows, curtains, etc. We hope to make the effect of distribution factors in daylight illumination (employing windows, skylights, etc.) the subject of a future study. In this study a photometric analysis of the illumination effects produced will be made an especial feature.

squares and illumination measurements were made at 66 of the intersections of the sides of these squares. Readings were taken in a plane 122 cm. above the floor with the receiving test plate of the illuminometer in the horizontal, the 45 deg. and 90 deg. positions measuring respectively the vertical, the 45 deg., and horizontal components of illumination. The 122 cm. plane was chosen because that was the height of the test object. (2) A determination was made of the brightness of prominent objects in the room, such as the test card, the reflectors for the semi-indirect installation, the reading page, the specular reflection from surfaces, etc. The brightness measurements were made by means of a Sharp-Millar illuminometer with the receiving test plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal on a white card. By this method the reflecting surfaces were used as detached test plates. The readings were converted into candle-power per sq. in. by the following formula:

$$\text{Brightness} = \text{Foot-candles}/\pi \times 144.$$

(3) Photographs were made of the room from three positions under each system of illumination.

A complete specification of the test room, the types of installation used, and the illumination effects produced for the systems of lighting, is given in the previous paper which appears elsewhere in this number of the TRANSACTIONS (pp. 413-422). Only such data will be repeated here as are necessary for reference.⁷

In Fig. 1 the test room is shown drawn to scale: plan of room, north, south, east and west elevations. In the drawing, plan of room, are shown the 66 stations at which the illumination measurements were made, and the positions of the outlets for the lighting fixtures, A, B, C, D, E, F, G, and H. In the drawing, east elevation, the observer in position at one of the points (Position I) at which the tests were taken is repre-

⁷ For a description of the test see the previous article referred to above (pp. 410-413); also Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort, TRANS. I. E. S., vol. VIII (1913), pp. 41-51.

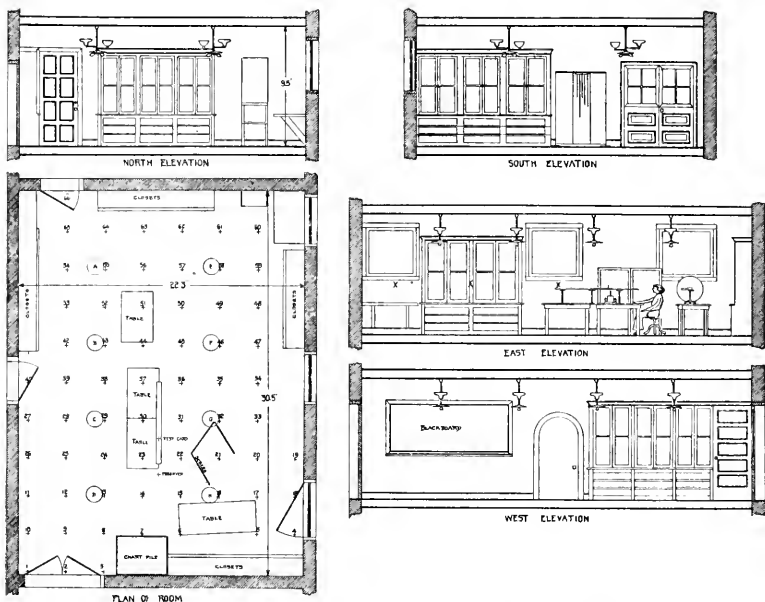


Fig. 1.—Plan of test room.

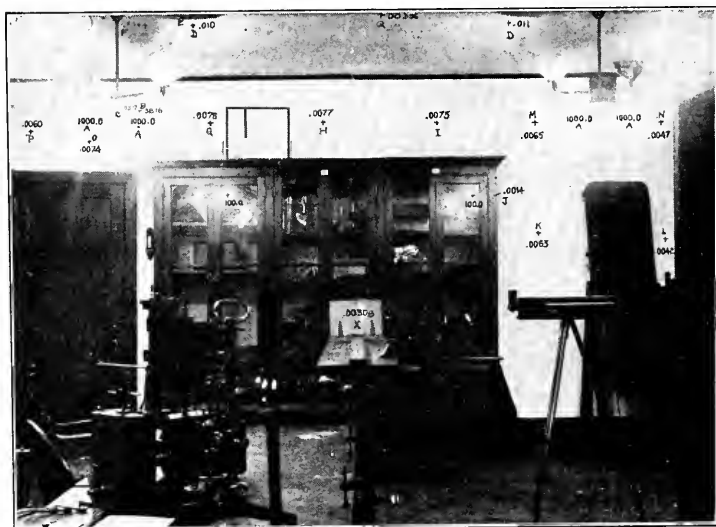


Fig. 2.—Showing brightness measurements of all surfaces having very high or very low brilliancy, direct system. The brightness of the printed page from which the observer read was, when held in the horizontal position, 0.0057 cp. per sq. in.; in the 45 deg. position, 0.004 cp. per sq. in.⁶

⁶ The bright spots on the doors of the apparatus case rated at 100 cp. per sq. in., shown in Fig. 2, were not in the field of view when the tests were taken. That is, when the tests were taken, the doors were thrown open, and all of the apparatus which might give specular reflection was removed.

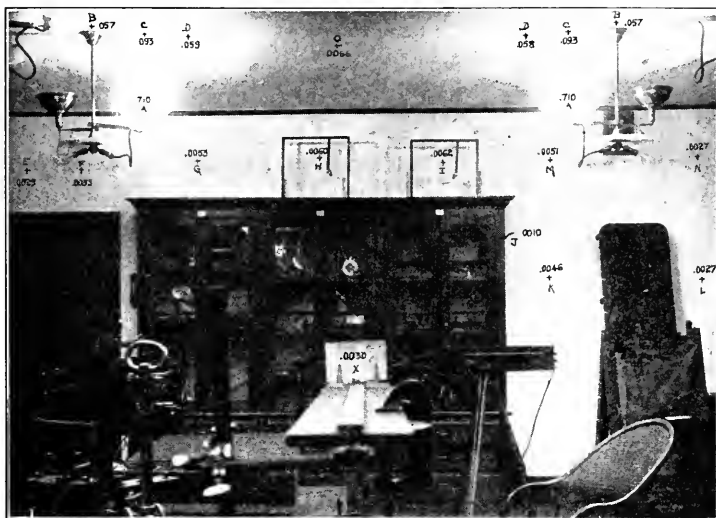


Fig. 3.—Showing brightness measurements of all surfaces having very high or very low brilliancy, semi-indirect system. The brightness of the printed page from which the observer read was, when held in the horizontal position, 0.0058 cp. per sq. in.; in the 45 deg. position, 0.0039 cp. per sq. in.

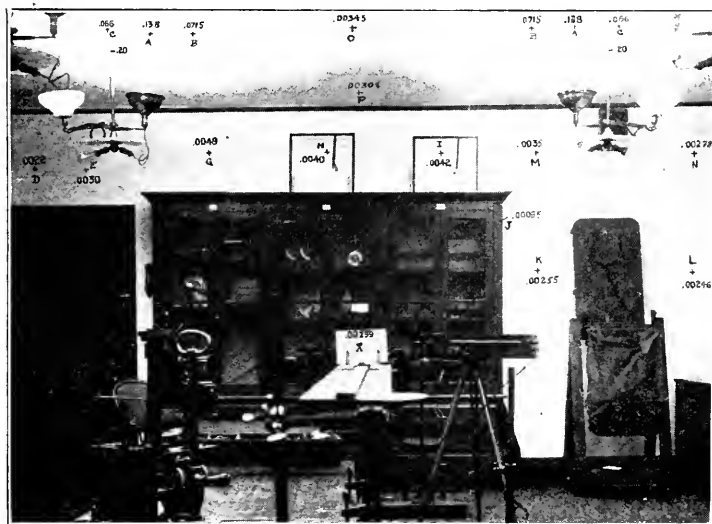


Fig. 4.—Showing brightness measurements of all surfaces having very high or very low brilliancy, indirect system. The brightness of the printed page from which the observer read was, when held in the horizontal position, 0.0088 cp. per sq. in.; in the 45 deg. position, 0.0043 cp. per sq. in.

sented.⁸ The other three positions are indicated in the photographs by (x). They will be referred to in the tables and charts, in order, by the numerals II, III, and IV.

Table I shows the number and wattage of the lamps used at the outlets A, B, C, D, E, F, G, and H; and Table II shows the illumination measurements for each of the 66 stations represented in Fig. I. These measurements were made with the receiving test plate of the photometer in the horizontal, vertical and 45 deg. planes.⁹

⁸ The track along which the test card was moved was parallel to the east and west walls of the room. During the three hours of reading which intervened between the two tests, the observer moved just far enough back from the upright supporting the mouth-board to give room for the book to be held and to permit of a comfortable reading position. The book was elevated and held approximately at an angle of 45 deg. When taking the test, the observer faced the north wall of the room, in such a position that with the eyes in the primary position, the lines of regard were parallel with the east and west walls of the room. Care was taken to have print of uniform size and distinctness for use with the three systems and to have a page which gave a comparatively small amount of specular reflection.

⁹ See also Table III, *The Efficiency of the Eye Under Different Conditions of Lighting, etc.*, TRANS. I. E. S., vol. X, 1915, p. 416a. This table was compiled as a supplement to Table II for the purpose of making a comparative showing of the evenness of illumination at the 122 cm. level given by the three systems of lighting. Two cases were made of this. (1) Comparisons were made of each component from station to station; (2) the difference between the components was compared. To facilitate these comparisons (a) the mean variation from the average of each of the components was computed; and (b) the difference between the averages of the three components was determined. The evenness of the illumination, it will be remembered, is not only of importance to the efficiency of the eye with reference to the object directly viewed; but also in its influence on the distribution of surface brightness. The evenness of surface brightness depends in general upon two sets of factors; (1) the nature and position of the reflecting surfaces in the room; and (2) the type of delivery of light to these surfaces.

We realize that the evenness of the illumination on the 122 cm. plane given by the indirect and semi-indirect units was somewhat interfered with by the reflectors of the direct system which were beneath and a little to the right of these units when in position for the test. Also the evenness of surface brightness on the ceiling for the direct system was interfered with by the indirect and semi-indirect reflectors which were above and a little to the side of the direct units. The influence of this "dead apparatus" will be eliminated in the next series of installations. Moreover, the installation in each case was not such as to give the best effects obtainable from the type of reflector used. For example, the indirect reflectors were too close to the ceiling to give the maximum evenness of illumination and surface brightness for the type of reflector employed. The analysis of the effects given in the former paper was not made, therefore, for the purpose of drawing general conclusions with regard to the type of reflector used. It was made solely for the sake of the comparison of the illumination effects obtained with the corresponding results for loss of efficiency.

TABLE I.

Showing the number and wattage of the lamps used at outlets

A, B, C, D, E, F, G and H.

Outlet	Direct Watts	Semi-indirect Watts	Indirect Watts
A	2-60	1-100	1-100
B	2-60	1-100	1-100
C	2-60	1-100	1-100
D	2-40	1-100	1-100
E	2-60	1-100	1-100
F	2-60	1-100	1-100
G	2-60	1-100	1-100
H	2-40	1- 60	1-100

TABLE II.—DISTRIBUTION SERIES.¹⁰

Showing the illumination measurements in foot-candles for each of the 66 stations represented in Fig. 1 for the direct, semi-indirect, and indirect systems used.

Station	Horizontal			Vertical			45°		
	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect
1	1.41	1.44	1.22						
2	1.32	1.47	1.26						
3	1.10	1.40	1.32						
4	1.37	1.10	1.47						
5	2.03	2.58	2.20						
6	2.50	3.20	2.95						
7	2.51	3.60	2.90						
8	3.30	3.75	3.00						
9	2.78	2.53	2.20						
10	1.50	1.59	1.35						
11	2.12	1.64	1.66						
12	4.20	2.65	2.70	0.47	0.48	0.47	2.40	1.25	1.43
13	6.10	5.25	4.10	0.47	0.48	0.42	3.30	2.25	1.96
14	3.70	4.95	4.40	0.48	0.47	0.47	2.00	2.40	2.30
15	3.00	4.85	4.50	0.44	0.48	0.47	1.97	1.88	2.30
16	6.60	4.25	4.10	0.70	0.37	0.48	3.58	1.60	2.10
17	4.65	2.35	3.15	0.48	0.24	0.46	1.80	0.69	1.60
18	2.15	1.69	2.20	0.49	0.38	0.47	1.10	0.66	1.63
19	2.95	2.10	2.50						
20	5.30	3.20	3.40	1.62	0.53	0.86	3.00	2.30	2.20
21	6.60	4.80	4.60	2.00	0.71	0.94	3.60	1.85	3.00
22	2.25	4.40	4.80	0.61	0.69	1.07	1.15	1.80	2.90
23	4.50	6.00	5.10	1.20	1.14	1.10	2.18	3.30	2.90
24	6.95	5.40	5.00	1.76	1.30	1.04	3.60	3.10	3.00
25	4.85	3.72	3.50	1.33	0.78	0.75	2.75	1.85	2.10
26	2.50	1.82	2.20						
27	2.81	2.05	2.40						
28	6.50	3.28	3.70	1.30	1.11	1.12	4.40	2.10	2.50
29	9.00	6.40	5.20	1.45	1.50	1.48	6.30	3.60	3.40
30	4.95	6.95	5.40	1.36	1.46	1.40	3.15	4.15	3.60
31	4.80	6.20	5.20	0.77	1.20	1.24	2.78	3.85	3.60

TABLE II.—DISTRIBUTION SERIES.--(Continued.)

Station	Horizontal			Vertical			45°		
	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect	Direct	Semi-indirect	Indirect
32	9.20	5.50	5.00	0.47	0.28	1.33	5.20	2.25	3.40
33	6.20	3.18	3.70	1.54	0.75	1.22	4.60	1.83	2.60
34	5.75	4.30	4.00	2.85	1.20	1.46	4.30	2.92	3.10
35	8.00	6.90	5.40	3.70	1.70	1.65	6.00	4.40	4.90
36	5.60	7.25	5.30	2.35	1.91	1.65	4.20	4.68	4.00
37	5.45	7.00	5.80	2.18	2.15	1.82	3.78	4.55	4.00
38	8.25	6.80	5.40	3.60	2.20	1.72	6.00	4.60	3.80
39	6.35	3.70	4.00	2.80	1.40	1.43	4.60	2.80	3.00
40	3.00	2.05	2.30						
41	2.70	1.73	2.10						
42	7.30	3.65	3.50	2.50	1.64	1.36	5.40	2.93	2.80
43	9.80	6.90	5.00	2.70	2.08	1.78	7.20	4.50	3.90
44	5.50	7.10	5.20	2.42	2.18	1.88	4.35	5.10	4.30
45	5.45	8.00	5.20	2.60	2.00	1.93	4.80	5.30	4.20
46	10.00	7.70	5.20	2.75	1.90	1.86	8.00	5.40	4.10
47	6.60	4.20	3.60	2.45	1.56	1.33	5.30	3.05	2.90
48	5.80	4.35	3.70	3.20	1.69	1.74	5.00	3.60	3.30
49	8.40	7.20	4.80	4.30	2.55	2.10	7.20	5.80	4.00
50	5.50	7.70	4.90	3.35	2.42	2.10	8.50	5.80	4.10
51	5.40	6.80	5.00	3.05	2.68	2.15	4.60	5.35	4.35
52	8.00	6.40	4.70	4.20	2.55	1.93	6.50	4.82	4.00
53	6.60	3.85	3.60	3.00	1.77	1.41	5.00	3.20	3.00
54	6.95	2.88	2.80	2.62	1.80	1.50	5.80	3.00	2.90
55	9.00	5.90	3.90	3.15	2.40	1.94	8.00	5.20	3.75
56	4.95	5.90	4.60	3.15	2.50	2.10	5.30	5.80	4.40
57	4.65	6.10	4.50	3.00	2.60	2.20	4.65	5.80	4.40
58	9.75	6.35	4.00	3.35	2.58	2.00	8.50	5.80	4.00
59	5.85	3.20	2.90	2.98	1.90	1.76	5.60	3.62	3.10
60	3.85	2.57	2.60			1.66			2.90
61	5.20	4.20	3.10	4.45	2.60	1.90	7.80	5.40	3.50
62	3.30	4.20	3.20	3.30	2.95	2.10	4.95	5.70	3.70
63	3.52	4.20	3.00	3.60	2.80	2.20	5.60	5.00	3.50
64	5.40	3.70	3.10	4.60	2.45	1.93	7.65	4.60	3.40
65	4.15	2.40	2.25	4.00	1.79	1.54	5.50	2.82	2.60
66	2.10	1.42	1.35						
Average	5.0	4.27	3.61	2.32	1.59	1.48	4.77	3.63	3.30

¹⁰ Reduced to equal wattages (800 watts) these installations give the following average illumination values in foot-candles for the receiving test plate in the positions specified above: Direct system: horizontal, 4.54; vertical, 2.2; 45°, 4.33. Semi-indirect system: horizontal, 4.49; vertical, 1.67; 45°, 3.82. Indirect: horizontal, 3.61; vertical, 1.48; 45°, 3.3.

It may not be out of place to suggest here that a careful study of the illuminating efficiency of different types of lighting units should be made under conditions that are strictly comparable for a wide range of variation. Such tests should be made under common supervision in a model room so constructed as readily to permit of the kind of variations needed; and should be, if possible, paralleled by tests for the efficiency of the eye. In working towards a reconstruction of lighting conditions, it is obvious that tests for the efficiency of the eye and for illuminating efficiency should go hand in hand.

Figs. 2, 3 and 4 are taken from the series of 9 photographs (see Figs. 2-10, op. cit., pp. 416b-416d) showing the illumination effects produced by the three systems of lighting. In these figures are given the brightness measurements of all surfaces having very high or very low brilliancy. The spot measured is indicated by a cross and the numerical value of the brightness measurement in candlepower per square inch is printed nearby. These spots are also lettered for convenience of reference in the intensity series. That is, since several installations were used in the intensity series, it was found convenient to express these values in tabular form and to identify them with the surfaces measured by means of letters. These photographs were taken from a point in line with the four positions of the observer as near to the south wall of the room as was possible; but owing to the narrow field of the camera as compared with the binocular field, these views include, for example, only about one-half of the field of vision of the observer at the test station nearest to this wall of the room. The camera's field in this position corresponds in fact very closely to the field presented to the observer seated at the center of the room. While, therefore, not all of his field of view for all of the positions at which tests were made is covered by the brightness measurements shown in the photographs, still the order of brightness difference present in the field of view for the different systems is well represented by these measurements, as can be seen by an inspection of the preceding photographs (see also Figs. 2-10, op. cit., pp. 416b-416d) and from the descriptions of the installations used. In order to facilitate certain features of comparison such as, for example, the evenness of surface brightness for each system for all of the room; for all of the room but the sources of light; and for all of the room but the sources and the spots above the sources, the brightness measurements shown in Figs. 2, 3 and 4 are also given in tabular form. These measurements and the letters identifying them with the surfaces measured, are given in Table III. In making the comparison it should be noted that the spots mentioned are not in all cases identical for the three systems. That is, owing to the different effects produced by the different reflectors, the same spots were not always conspicuously light or dark for the three systems. The letters, E,

F, G, etc., may then refer to entirely different spots in case of the three systems.

TABLE III.—DISTRIBUTION SERIES.

Showing the brightness measurements in candlepower per square inch for the surfaces A, B, C, D., etc., see Figs. 2, 3 and 4.

Surface measured	Direct system	Semi-indirect system	Indirect system
A	1000.0000	0.710	0.138
B	0.3816	0.057	0.0715
C	0.517	0.093	0.066
D	0.010	0.059	0.0022
E	0.00296	0.0029	0.0030
F	0.0044	0.0033	0.00123
G	0.0078	0.0053	0.0049
H	0.0077	0.006	0.0040
I	0.0075	0.0062	0.0042
J	0.0014	0.0010	0.00095
K	0.0063	0.0046	0.00255
L	0.0042	0.0027	0.00246
M	0.0065	0.0051	0.00352
N	0.0047	0.0027	0.00272
O	0.0074	0.0066	0.00343
P	0.006	0.00484	0.00308
Q	0.00396		

TABLE IV.—DISTRIBUTION SERIES.

Showing the brightness measurements in candlepower per sq. in. of the test card, reading page horizontal, and reading page in the 45 deg. position for Positions I, II, III, and IV, for the direct, semi-indirect, and indirect systems.

Position of observer	Surface measured	Direct system	Semi-indirect system	Indirect system
I	Test card.....	0.00308	0.0030	0.00299
	Reading page horizontal....	0.0057	0.0058	0.0088
	Reading page 45° position...	0.004	0.0039	0.00431
II	Test card.....	0.00506	0.00453	0.0046
	Reading page horizontal....	0.0088	0.0107	0.0088
	Reading page 45° position...	0.0068	0.00726	0.00792
III	Test card.....	0.0055	0.00462	0.00453
	Reading page horizontal....	0.0092	0.0087	0.00814
	Reading page 45° position...	0.00704	0.0077	0.00594
IV	Test card....	0.0066	0.00475	0.00453
	Reading page horizontal....	0.00814	0.00572	0.00572
	Reading page 45° position...	0.0063	0.00484	0.00484

In Table IV are given the brightness measurements in candlepower per square inch for the test card and the reading page for the four positions of the observer: I, II, III and IV, for the direct, semi-indirect and indirect systems. The measurements of the reading page were taken at the point of work for the four positions of the observer with the book in the horizontal and 45 deg. position. During work the book was held in the 45 deg. position.

In Tables V and VI are shown some prominent ratios of sur-

face brightness for the three systems.¹¹ (See also Table VIII, op. cit., p. 421.)¹²

In compiling these ratios it has been considered important to make a comparative showing for the three systems (a) of the extremes of surface brightness; and (b) of the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work. The extremes of surface brightness

¹¹ In attempting to make comparisons of the effect of the different magnitudes of brightness ratios, one obviously must bear in mind that the surfaces between which the ratios are established are not in all cases in the same position in the field of vision for the three systems. For example, the brightest surfaces in case of the indirect system, namely, the spots on the ceiling directly above the reflectors, are farther removed from the direct line of vision of the observer in the working position than were the brightest surfaces in case of the direct and semi-indirect systems. The position of the surface in the field of vision would come into question, for example, in making a determination of the maximum value of brightness difference the eye is adapted to stand. While we have done a great deal of work on the effect of position of the brilliant surface in the field of vision in our investigation of the causes of discomfort, we have made no especial investigation of this point in relation to loss of efficiency. Doubtless what we shall all have to bear in mind is that, even in the end, we cannot hope to specify narrowly what is most favorable, etc. In lighting conditions. The factors that enter into the concrete lighting situation are so complex or rather are so variable and so rarely duplicated that we can hope to make general specifications with regard to what is most favorable, for example, only within very broad limits. If one wishes to work the conditions down to a finer point than this, the particular installation must be tested *in situ*. We are at present working on a test which we hope will serve this purpose better than the test which has been used in the work described in the preceding papers.

¹² Table VIII, (op. cit., p. 421) was compiled from Tables IV-VII of that paper to show the mean variation in surface brightness for all the surfaces measured for the direct, semi-indirect, and indirect systems. In referring back to that paper it may not be out of place to call to mind again that the percentages given in Table VIII seem to indicate that the great advantage of the indirect over the other systems of lighting we have used with regard to the factor, evenness of surface brightness, comes, primarily at least, from its provisions for shielding the eye from the light source rather than from any conspicuously greater evenness of illumination given by it to the objects in the field of view. In fact, as may be seen from that table, all the systems give a fairly even distribution of surface brightness outside of the source and the surfaces immediately surrounding it.

The need of keeping surface brightness within certain limits and the primary importance of properly shielding the eye from the source, to the accomplishment of this desideratum, are obvious. Doubtless many ways will be devised in course of time for cutting down useless and harmful brightness differences in lighting effects. For example, the possibility is here suggested of producing a still smaller brightness difference than is given by the indirect reflectors of the type we have employed, by using semi-indirect reflectors of such a density as to give a surface brilliancy equal to that of the spot of light cast upon the ceiling. The value of this brilliancy, because of the larger area of luminous surface presented, could then be made smaller than that of the ceiling spot cast by the indirect reflector and still give the same amount of light to the room. A similar effect may be obtained with the indirect reflector by using lamps of lesser wattage and adding the light needed to make up the deficiency by installing directly beneath the reflector lamps of low wattage in translucent enclosures of a density that gives a surface brilliancy equal to that of the ceiling spots. The effect of both of these devices would be to lower the surface brilliancy for a given light flux by increasing the area of the luminous surface. Whether either device would be advisable from other standpoints we are not at present prepared to say.

are shown by giving the ratios between surfaces of the first, second, third, etc., order of brilliancy and the surface of the lowest order of brilliancy; and the comparison of the brilliancy of objects in the surrounding field to the brightness at the point of work by giving the ratios of the surfaces of the first, second, and third order of brilliancy to the brightness of the test card and the reading page in the working position. The following points may be noted. (1) The illumination effects produced by the direct system are characterized by great extremes of surface brightness, and a high ratio of brilliancy of objects in the surrounding field to the surface brightness at the point of work. These effects are much less pronounced for the semi-indirect system and still less for the indirect. (2) A comparison of this table with the tables giving loss of efficiency as the result of work shows that while the extremes of surface brightness are enormously larger for the direct than for the semi-indirect system, the eye loses almost as much in efficiency for three hours of work under the semi-indirect as under the direct system. That is, the greatest ratio of brightness for the direct system is over one thousand times as much as the greatest ratio for the semi-indirect, while the difference in loss of efficiency for the two systems is comparatively insignificant. On the other hand, the greatest ratio of brightness for the semi-indirect system is only about five times as much as for the indirect; while the difference in loss of efficiency for three hours of work is very large, this loss of efficiency for three hours of work for the indirect system being, it will be noted, very small indeed. This seems to indicate (a) that for the scale of brightness magnitudes and the illumination effects present in this series of experiments the gradation of surface brightness for the indirect system is very close to what the eye is adapted to stand without loss of efficiency; and (b) that an increase in difference in brightness above this point is followed at first by a rapid increase in loss of efficiency and later by a much slower increase. In the intensity series, in the work of the former paper, it will be remembered, the following points also came out. (1) The effect of size of ratio on loss of efficiency is different for different orders of magnitude of brightness. And (2) the size of the brilliant object, as

well as its brilliancy, is of importance. That is, within certain limits, as yet undefined, an increase in the area of the brilliant surface causes an increase in loss of efficiency.

In Table V the ratios were compiled from measurements showing the extremes of brightness of prominent surfaces in the room. In Table VI they were compiled to show the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work for the positions of the observer, I, II, III and IV¹³ (see Fig. 1, p. 452a). In general a falling off in the magnitude of brightness differences in the field of view will be noted in order from the Positions I to IV. This falling off is greatest for the direct system, next greatest for the semi-indirect, and least for the indirect. Thus there is not only a decrease in the number of surfaces in the field of view showing a high brilliancy from Positions I to IV, but also a decrease in the magnitude of brightness difference between the surfaces of high brilliancy and the test card, between these surfaces and the reading page, etc., especially for the direct and semi-indirect systems. An inspection of the table for loss of efficiency shows, roughly speaking, a correspondingly marked decrease in loss of efficiency from Positions I to IV for the systems which show the marked decrease in brightness difference, that is, for the direct and semi-indirect systems. The decrease in loss of efficiency, it will be noted, is practically nothing for the indirect system. Thus not only much less loss of efficiency is sustained by the eye for the indirect units used, but the results are much more independent of the position of the observer in the room.

The loss of efficiency for the Positions I, II, III and IV for the three systems is shown in Table VII.¹⁴

¹³ It may also be of interest to the reader to work out for these four positions the ratios: lightest to darkest, darkest to test card, darkest to reading page, etc.

¹⁴ Obviously in the consideration of the effect of a given lighting situation on the ability of the eye to hold its efficiency for a period of work, the age of the observer and the condition of his eyes should be taken into account. All the observers that have been employed by us in this work were under 26 years of age. Following is a clinic report of the eyes of the observer whose results are given in the following table, made by Dr. Wm. Campbell Posey of Philadelphia.

Observer R.

With glasses.—Vision of right eye = 20/25. Far muscle test = 0 ½ esophoria.

Vision of left eye = 20/20- Near muscle test = orthophoria.

Ophthalmoscopic examination.—Right eye = mixed astigmatism, ½ diopter.

Left eye = hyperopic astigmatism, 1½ diopters.

(Continued on next page.)

Chart I gives a graphic representation of the results of this table. Loss of efficiency is plotted along the ordinate and time of work along the abscissa. Each of the large squares along the abscissa represents an hour of work and along the ordinate an integer of the ratio, time clear to time blurred. The effect on loss of efficiency of the number and magnitude of brightness of surfaces of high brilliancy, especially of primary sources, in the field of view is obvious from these charts. The chart for position IV, however, shows that there is still a considerable difference in the loss of efficiency produced by the three systems, even when there are no sources or other surfaces of high brilliancy in the field of view. The indirect system still gives the least loss of efficiency, the semi-indirect next, and the direct the most. As may be seen in Figs. 2, 3, and 4, and in Tables III and VI there was little difference in the evenness of surface brightness in the field of view presented to the observer in this position, certainly none that could be considered of consequence in favor of the indirect system. The above results seem to indicate, therefore, that while the evenness of surface brightness is an important factor it is not the only factor in a lighting situation which may influence the amount of loss of efficiency sustained by the eye as the result of a period of work.

We wish to repeat in this paper what was very strongly emphasized in our former paper, namely, that the units we have employed were not selected as fully representative of the classes direct, semi-indirect, and indirect. Agreement in fact has not yet been reached with regard to what falls within each of these

External condition.—Adduction good; eyes slightly divergent under cover; cornea clear; pupils, $2\frac{1}{2}$ mm.; irides respond equally and freely to light, accommodation, and convergence stimuli.

Glasses worn during test.—Right eye = —S., 0.50 D.;—C., 0.37D., x 160°

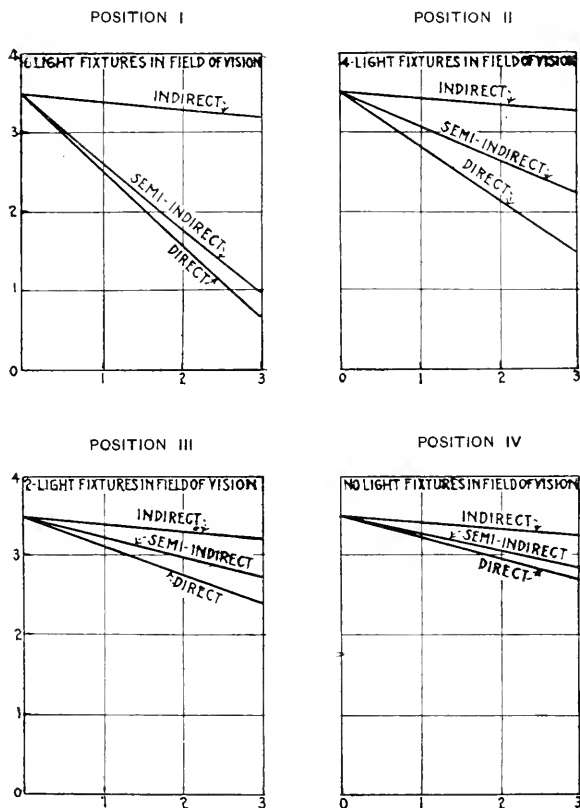
Left eye = —C., 0.50 D., x 180°

Lest the former paper has not appeared in print before this one is presented it may be well to make some mention here also of the reproducibility of results that may be obtained for our test for loss of efficiency. The mean variation of the ratio, time clear to time blurred for the same observer working under conditions as nearly constant as possible, is very small indeed. The order of magnitude of the mean variation of the test for the fresh eye was obtained as follows. Beginning at 9 A. M. five 3 minute tests were run with a rest period of 20 minutes between each test. This was done with all observers on several days under each system of lighting employed. The rest period was taken in each case in a room lighted by daylight, with the observer facing a wall with an evenly lighted matt surface. For a single series of five tests the variation in the time seen clear in the 3 minute periods have always fallen within 1 per cent. for all of the observers we have used and for all systems of lighting.

classes. The units employed were chosen rather to show the effect of varying the factors we have grouped under the heading of distribution on the ability of the eye to maintain its efficiency for a period of work. We hope ultimately to determine the

CHART I.—DISTRIBUTION SERIES.

Showing the effect on loss of efficiency of varying the observer's position in the room, or the number of bright sources, primary and secondary, in the field of vision.



limits between which each of these factors may vary in a selected range of lighting situations, without damage to the eye, especially the factor surface brightness. These most favorable conditions will then serve as a goal to be attained whatever principal of lighting is employed.

TABLE V.—DISTRIBUTION SERIES.
Ratios showing the extremes of surface brightness for the direct, semi-direct, and indirect systems used.

Ratio	Direct system	Semi-indirect system	Indirect system
Lightest to darkest.....	1000/0.0014 = 714,285	0.710 /0.001 = 710	0.138 /0.00095 = 145
2nd lightest to darkest.....	... 0.3816/0.0014 = 123.9	0.093 /0.001 = 93.0	0.0715 /0.00095 = 75.2
3rd lightest to darkest.....	... 0.0517/0.0014 = 37.0	0.059 /0.001 = 59.0	0.066 /0.00095 = 69.4
4th lightest to darkest ... ..	... 0.01 /0.0014 = 7.14	0.057 /0.001 = 57.0	0.0049 /0.00095 = 5.15
5th lightest to darkest ....	... 0.0078/0.0014 = 5.57	0.0066 /0.001 = 6.6	0.0042 /0.00095 = 4.42
6th lightest to darkest ....	... 0.0077/0.0014 = 5.50	0.0062 /0.001 = 6.2	0.0040 /0.00095 = 4.21
7th lightest to darkest .....	... 0.0075/0.0014 = 5.35	0.0060 /0.001 = 6.0	0.00352/0.00095 = 3.70
8th lightest to darkest .....	... 0.0074/0.0014 = 5.28	0.0053 /0.001 = 5.3	0.00343/0.00095 = 3.61
9th lightest to darkest .....	... 0.0065/0.0014 = 4.64	0.0051 /0.001 = 5.1	0.00308/0.00095 = 3.24
10th lightest to darkest .....	... 0.0063/0.0014 = 4.5	0.00484/0.001 = 4.84	0.0030 /0.00095 = 3.15
11th lightest to darkest .....	... 0.006 /0.0014 = 4.28	0.0046 /0.001 = 4.6	0.00255/0.00095 = 2.68
12th lightest to darkest .....	... 0.0047/0.0014 = 3.36	0.0033 /0.001 = 3.3	0.00246/0.00095 = 2.57
13th lightest to darkest .....	... 0.00404/0.0014 = 3.14	0.0029 /0.001 = 2.9	0.0022 /0.00095 = 2.31
14th lightest to darkest .....	... 0.0042/0.0014 = 3.00	0.0027 /0.001 = 2.7	0.00123/0.00095 = 1.29

TABLE VI.—DISTRIBUTION SERIES.

Ratios showing the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work for Positions I, II, III, and IV for the direct, semi-indirect, and indirect systems used.

Position of observer	Ratio	Direct system	Semi-indirect system	Indirect system
I	Lightest to test card.....	1000/0.00308 = 324,674	0.710 /0.003 = 236.7	0.138 /0.00299 = 46.0
	Lightest to reading page.....	1000/0.004 = 250,000	0.710 /0.0039 = 182.0	0.138 /0.00431 = 32.0
	2nd lightest to test card.....	0.3816/0.00308 = 123.9	0.093 /0.003 = 31.0	0.0715 /0.00299 = 24.0
	2nd lightest to reading page.....	0.3816/0.004 = 95.3	0.093 /0.0039 = 24.0	0.0715 /0.00431 = 16.5
	3rd lightest to test card.....	0.0517/0.00308 = 16.8	0.059 /0.003 = 29.7	0.066 /0.00299 = 22.0
	3rd lightest to reading page.....	0.0517/0.004 = 12.9	0.059 /0.0039 = 15.0	0.066 /0.00431 = 15.0
II	Lightest to test card.....	1000/0.00506 = 197,628	0.710 /0.00453 = 156.7	0.138 /0.0046 = 30.0
	Lightest to reading page.....	1000/0.0068 = 147,059	0.710 /0.00726 = 97.8	0.138 /0.00792 = 17.0
	2nd lightest to test card.....	0.3816/0.00506 = 75.4	0.093 /0.00453 = 20.5	0.0715 /0.0046 = 15.5
	2nd lightest to reading page.....	0.3816/0.0068 = 56.0	0.093 /0.00726 = 12.8	0.0715 /0.00792 = 9.0
	3rd lightest to test card.....	0.0517/0.00506 = 10.2	0.059 /0.00453 = 13.0	0.066 /0.0046 = 14.3
	3rd lightest to reading page.....	0.0517/0.0068 = 7.6	0.059 /0.00726 = 8.0	0.066 /0.00792 = 8.0
III	Lightest to test card.....	1000/0.0035 = 181,818	0.710 /0.00462 = 154.0	0.138 /0.00453 = 30.4
	Lightest to reading page.....	1000/0.00704 = 142,055	0.710 /0.0077 = 92.0	0.138 /0.00594 = 23.0
	2nd lightest to test card.....	0.3816/0.0035 = 69.0	0.093 /0.00462 = 26.0	0.0715 /0.00453 = 15.8
	2nd lightest to reading page.....	0.3816/0.00704 = 54.0	0.093 /0.0077 = 12.0	0.0715 /0.00594 = 12.0
	3rd lightest to test card.....	0.0517/0.0035 = 9.0	0.059 /0.00462 = 12.8	0.066 /0.00453 = 12.0
	3rd lightest to reading page.....	0.0517/0.00704 = 0.7	0.059 /0.0077 = 7.7	0.066 /0.00594 = 11.0
IV	Lightest to test card.....	0.0063/0.0066 = 0.954	0.00484/0.00175 = 1.019	0.00484/0.00453 = 1.068
	Lightest to reading page.....	0.0066/0.0063 = 1.047	0.00475/0.00484 = 0.785	0.00453/0.00484 = 0.936
	2nd lightest to test card.....	0.0014/0.0066 = 0.212	0.010 /0.00475 = 0.0210	0.00095/0.00453 = 0.209
	2nd lightest to reading page.....	0.0014/0.0063 = 0.222	0.010 /0.00484 = 0.00207	0.00095/0.00484 = 0.196

TABLE VII.—DISTRIBUTION SERIES.

Showing the effect on loss of efficiency of varying the observer's position in the room, or the number of light sources primary and secondary, in the field of vision. At Position I, six light fixtures were in the field of vision; at Position II, four light fixtures; at Position III, two light fixtures; and at Position IV, no light fixtures.

Position of observer	Lighting system	Watts	Volts	Intensity foot-candles		Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear + blurred	Ratios reduced to comm-standard
				Hori-zontal	Verti-cal							
I.	Indirect.....	800	107	5.2	1.36	3.5	84.5	67.5	135	45	3.0	3.5
						12 M.	84.5	67.5	132	48	2.75	3.2
	Semi-indirect	760	107	5.8	1.45	4.0	80.5	68.5	142	38	3.73	3.5
II.	Direct	880	107	4.2	1.41	2.6	79.5	68.5	92	88	1.04	0.97
						9 A.M.	81.0	68.0	139	41	3.39	3.5
						12 M.	78.0	68.0	71	109	0.65	0.67
III.	Indirect.....	800	107	5.1	1.98	4.2	86.5	74.0	141	39	3.61	3.5
						12 M.	86.5	74.0	139	41	3.39	3.28
	Semi-indirect	760	107	6.1	2.5	4.7	87.0	75.0	138	42	3.28	3.5
IV.	Direct	880	107	4.65	2.75	4.4	87.0	75.0	123	57	2.19	2.2
						9 A.M.	87.0	75.0	134	46	2.91	3.5
						12 M.	84.0	75.0	99	81	1.22	1.46
V.	Indirect.....	800	107	3.9	2.1	4.0	84.0	70.0	130	50	2.6	3.5
						9 A.M.	84.0	70.0	127	53	2.4	3.23
	Semi-indirect	760	107	5.0	2.6	5.4	84.0	69.0	131	49	2.67	3.5
VI.	Direct	880	107	4.0	2.9	4.6	84.0	69.0	122	58	2.1	2.73
						9 A.M.	83.5	70.0	148	32	4.6	3.5
						12 M.	83.0	70.0	137	43	3.8	2.41
VII.	Indirect.....	800	107	2.9	2.1	3.6	84.0	70.0	139	41	3.39	3.5
						12 M.	84.0	70.0	137	43	3.18	3.27
	Semi-indirect	760	107	3.4	3.0	4.4	83.5	70.5	139	41	3.39	3.8
VIII.	Direct	880	107	3.0	3.4	4.5	83.5	69.0	132	48	2.75	2.83
						9 A.M.	82.0	69.0	119	61	1.95	3.5
						12 M.	81.0	69.0	108	72	1.5	2.7

As was also stated in our former paper our next step in this division of the work will be to determine by using reflectors of different degrees of opacity the effect on loss of efficiency when the light is distributed to the plane of work both by the direct and indirect principles of lighting. That is, reflectors of different densities: prismatic, alba, opal lux, totally opaque, etc., will be used turned up and down. In each case the installation will be made with special reference to giving the best results obtainable for the particular type of unit employed; and the factors: evenness of illumination, diffuseness of light, the angle at which the light falls on the work, and the evenness of surface brightness, will be varied separately in turn and the effect on loss of efficiency will be determined. Moreover, if it is found that the factors in question cannot be studied in sufficient detail in the concrete lighting situation, the work will be supplemented by more abstract investigations. The results of this series of tests should give us among other things, for example, a still better idea of what amount of brightness difference the eye is adapted to stand, and the comparative effect of different ratios of surface brightness on loss of efficiency.

INTENSITY SERIES.

In the work of the preceding paper we had undertaken to determine the most favorable intensities for the three types of artificial lighting we had used in the distribution series, and the effect of varying intensity with the particular grouping of distribution factors represented in each case. As was stated in the introduction of the present paper, this work was completed for the direct and semi-indirect systems but not for the indirect. For the semi-indirect installation it will be remembered that the eye fell off heavily in efficiency for all intensities with the exception of a very narrow range on either side of 2.2 foot-candles, measured at the point of work with the receiving test plate of the photometer in the horizontal plane. For the direct installation no intensity could be found for which the eye did not lose a great deal in efficiency as the result of work. For the indirect installation, however, as the following data will show, a comparatively wide range of intensity may be used without the eye suffering

any considerable loss of efficiency as the result of three hours of continuous work.

The tests were made in the same room, with the same fixtures, and in general, with the same conditions of installation and methods of working as were described in the work on the distribution factors. To secure the various degrees of intensity needed, lamps of different wattage were employed. These were selected from a series of tungsten lamps ranging from 15 to 100 watts. In order to keep the distribution factors as nearly constant as possible for a given type of system, the lamps used in making the test for that type of system were all of one wattage, *i. e.*, were all 15's, 25's, 40's, 60's or 100's.

For the indirect system the total range of intensity employed is shown by the following figures. The series was begun with 25-watt lamps, and consisted of 25, 40, 60, and 100-watt lamps. For the 25 watt lamps the photometer reading at the point of work with the receiving test plate in the horizontal plane showed 1.33 foot-candles of light; with the receiving test plate in the vertical plane, 0.39 foot-candle; and with the receiving test plate in the 45 deg. plane, 0.87 foot-candle. For the 100-watt lamps 5.2 foot-candles were obtained with the receiving test plate in the horizontal plane; 1.36 foot-candles with the test plate vertical; and 3.5 foot-candles with the test plate inclined 45 deg. The tests for loss of efficiency¹⁵ showed probably a slight advantage for the 25-watt lamps, although the difference in result for the different intensities is sufficiently near in value to the mean variation of the test as to be scarcely worthy of consideration.

As was the case for the direct and semi-indirect installations, the following specification was made of the illumination effects produced by the indirect installation. (1) Illumination measure-

¹⁵ In conducting these tests it was found necessary to allow a period of adaptation without work, to the illumination of the room before the first test was taken. If this were not done, especially in case of the lower intensities of lights used, the changing sensitivity of the eye to the intensity of light employed, produced a noticeable change in the visual acuity between the times the tests before and after work were taken. Since the distance of the test card was kept the same for the two tests, this change in the visual acuity tended to influence the ratio, time clear to time blurred. To determine the length of time needed under a given intensity of light to insure a constant acuity, so far as adaptation is concerned, preliminary tests were made as follows. The acuity of the observer was taken every 3 minutes until no noticeable change was found. This length of time was then always allowed for that observer as an adaptation period prior to the loss of efficiency test conducted for the given intensity of illumination.

ments were made for the highest intensity employed at the 66 stations in the test room. These measurements were made in the way described in the preceding section. For the other intensities used, measurements were made at nine representative stations to show in a general way the order of magnitude of reduction produced by using the lamps of lower wattage. (2) Brightness measurements were made of the prominent objects in the room, such as the test card, the book of the observer, and all surfaces showing very high or very low brilliancy for all of the intensities.

In Table VIII are given the illumination measurements at the 66 stations for the highest wattages used, made with the receiving test plate of the photometer in the horizontal, vertical, and 45 deg. planes. Tables IX and X show the illumination measurements at the nine representative stations for the other wattages employed in the series. The order of magnitude of reduction of the illumination of the room produced by using the lamps of lower wattage conforms pretty closely in each case, it will be observed, to the simple ratio of the wattages employed. (See foot-note to Table XII, p. 472.) As was the case for the semi-indirect system, noted in the preceding paper, socket extenders had to be used with the 25 and 40-watt lamps. That is, without the extenders these lamps, owing to their smaller size, came so low in the reflector as to change the distribution effects given by reflectors. For example, without the socket extenders for these shorter lamps, the spot of light on the ceiling was made smaller and correspondingly more brilliant. It was thought advisable to determine whether this comparatively small change in illumination effects would cause any difference in the eye's ability to hold its efficiency for a period of work. In the specification of illuminating effects, therefore, measurements have been made for the 25 and 40-watt lamps both with and without socket extenders. In Table IX illumination measurements for the 25 and 40-watt lamps are given with socket extenders, and in Table X illumination measurements for these lamps are given without socket extenders. In Table XI are given the brightness measurements for the indirect installation for the different intensities used, both with and without socket extenders for the 25 and 40-watt lamps.

The points at which the measurements were taken are indicated by the letters A, B, C, D, E, F, etc., see Fig. 4, p. 452b. In Table XII are given the prominent brightness ratios for the different intensities used. Obviously an important point of comparison for the purposes of this investigation is the ratios with and without socket extenders for the 25 and 40-watt lamps.

TABLE VIII.—INTENSITY SERIES.

Showing the illumination measurements in foot-candles for each of the 66 stations represented in Fig. 1 for the indirect system used.

Station	Horizontal	Vertical	45°	Station	Horizontal	Vertical	45°
1	1.22	—	—	34	4.0	1.46	3.1
2	1.26	—	—	35	5.4	1.65	4.9
3	1.32	—	—	36	5.3	1.65	4.0
4	1.47	—	—	37	5.8	1.82	4.0
5	2.2	—	—	38	5.4	1.72	3.8
6	2.95	—	—	39	4.0	1.43	3.0
7	2.9	—	—	40	2.3	—	—
8	3.0	—	—	41	2.1	—	—
9	2.2	—	—	42	3.5	1.36	2.8
10	1.35	—	—	43	5.0	1.78	3.9
11	1.66	—	—	44	5.2	1.88	4.3
12	2.7	0.47	1.43	45	5.2	1.93	4.2
13	4.1	0.42	1.96	46	5.2	1.86	4.1
14	4.4	0.47	2.3	47	3.6	1.33	2.9
15	4.5	0.47	2.3	48	3.7	1.74	3.3
16	4.1	0.48	2.1	49	4.8	2.1	4.0
17	3.15	0.46	1.6	50	4.9	2.1	4.1
18	2.2	0.47	1.63	51	5.0	2.15	4.35
19	2.5	—	—	52	4.7	1.93	4.0
20	3.4	0.86	2.2	53	3.6	1.41	3.0
21	4.6	0.94	3.0	54	2.8	1.5	2.9
22	4.8	1.07	2.9	55	3.9	1.94	3.75
23	5.1	1.1	2.9	56	4.6	2.1	4.4
24	5.0	1.04	3.0	57	4.5	2.2	4.4
25	3.5	0.75	2.1	58	4.0	2.0	4.0
26	2.2	—	—	59	2.9	1.76	3.1
27	2.4	—	—	60	2.6	1.66	2.9
28	3.7	1.12	2.5	61	3.1	1.9	3.5
29	5.2	1.48	3.4	62	3.2	2.1	3.7
30	5.4	1.4	3.6	63	3.0	2.2	3.5
31	5.2	1.24	3.6	64	3.1	1.93	3.4
32	5.0	1.33	3.4	65	2.25	1.54	2.6
33	3.7	1.22	2.6	66	1.35	—	—
				Average	3.61	1.48	3.3

TABLE IX.—INTENSITY SERIES.

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the indirect system. Socket extenders used with the 40 and 25-watt lamps.

Station	Horizontal				Vertical				45°			
	800	480	320	200	800	480	320	200	800	480	320	200
Card	5.2	3.0	1.7	1.33	1.36	0.765	0.49	0.39	3.5	1.97	1.08	0.87
12	2.7	1.63	0.97	0.65	0.47	0.265	0.18	0.12	1.43	0.83	0.48	0.44
16	4.1	2.2	1.32	1.11	0.52	0.33	0.24	0.14	2.1	1.22	0.66	0.6
31	5.2	2.7	1.84	1.45	1.24	0.77	0.51	0.47	3.6	1.95	1.16	1.01
34	4.0	2.25	1.21	1.0	1.46	0.79	0.52	0.49	3.1	1.63	0.89	0.78
39	4.0	2.2	1.6	0.83	1.43	0.725	0.51	0.37	3.0	1.57	1.04	0.64
45	5.2	2.75	1.94	1.28	1.93	0.99	0.58	0.53	4.2	2.18	1.43	1.0
54	2.8	1.48	1.16	0.68	1.5	0.82	0.63	0.41	2.9	1.51	1.23	0.68
58	4.0	2.1	1.3	1.09	2.0	0.94	0.64	0.52	4.0	2.2	1.3	0.98
Ave.	3.61	2.16	1.44	0.9	1.32	0.89	0.59	0.37	3.3	1.98	1.32	0.83

TABLE X.—INTENSITY SERIES.

Showing the illumination measurements in foot-candles at nine representative stations for the different intensities used for the indirect system. No socket extenders used with the 40 and 25-watt lamps.

Station	Horizontal				Vertical				45°			
	800	480	320	200	800	480	320	200	800	480	320	200
Card	5.2	3.0	1.48	1.16	1.36	0.765	0.407	0.37	3.5	1.97	0.95	0.76
12	2.7	1.63	0.84	0.5	0.47	0.265	0.139	0.99	1.43	0.83	0.44	0.282
16	4.1	2.2	1.01	0.96	0.52	0.33	0.143	0.14	2.1	1.22	0.5	0.48
31	5.2	2.7	1.48	1.3	1.24	0.77	0.462	0.39	3.6	1.95	1.0	0.86
34	4.0	2.25	0.99	1.0	1.46	0.79	0.5	0.45	3.1	1.63	0.84	0.8
39	4.0	2.2	1.63	0.78	1.43	0.725	0.44	0.36	3.0	1.57	0.98	0.6
45	5.2	2.75	1.62	1.18	1.93	0.99	0.52	0.48	4.2	2.18	1.31	0.98
54	2.8	1.48	1.03	0.63	1.5	0.82	0.61	0.41	2.9	1.51	1.18	0.65
58	4.0	2.1	1.11	0.87	2.0	0.94	0.54	0.42	4.0	2.2	1.11	0.83

The results of the tests for the intensity series for the indirect system are given in Table XIII. Three hours was selected as the period of work in all of these experiments. The tests were taken only as Position I (see Fig. 1, p. 452a), the position, it will be remembered, at which six of the fixtures were in the field of view. It will be noted that there is practically no difference in the loss of efficiency of the eye for the different intensities of illumination when socket extenders were used for the shorter lamps. When socket extenders were not used for these lamps, quite a little loss of efficiency was experienced. This loss, moreover, was considerably greater for the shorter 25-watt lamps than for the 40-watt

lamps. Since the prominent variable in this case was intrinsic brilliancy of the ceiling spot above the reflector, the increased loss of efficiency can probably be ascribed primarily to this cause; or more comprehensively stated perhaps, to the change in the magnitude of the brightness differences that were present in the field of vision. For example, the ratio, lightest to darkest for the 100-watt lamps was 145; it was 133 for the 60-watt lamps; 142 for the 40-watt lamps with socket extenders; and 135 for the 25-watt lamps with socket extenders. For the 40-watt lamps without socket extenders, however, this ratio was raised to 326, and for the 25-watt lamps without socket extenders it was raised to 374. Similar changes were also made in the other ratios: lightest to test card, lightest to reading page, etc., as may be seen by inspecting Table XII.

TABLE XI.—INTENSITY SERIES.

Showing the brightness measurements in candlepower per square inch for the different intensities used for the indirect system at points indicated by the letters A, B, C, D, etc., see Fig. 4.

Surface measured	800 watts	480 watts	320 watts		200 watts	
			With socket extenders	Without socket extenders	With socket extenders	Without socket extenders
A.....	0.138	0.0704	0.0539	0.088	0.0352	0.0748
B.....	0.0715	0.0385	0.0252	0.0231	0.0165	0.0187
C.....	0.066	0.0352	0.0244	0.022	0.0159	0.0165
D.....	0.0022	0.00097	0.00079	0.00059	0.00064	0.0004
E.....	0.0030	0.000163	0.00119	0.0007	0.00084	0.00057
F.....	0.00123	0.000401	0.00035	0.00022	0.00032	0.00018
G.....	0.0049	0.00169	0.00145	0.00101	0.00128	0.00084
H.....	0.0040	0.00163	0.00129	0.00092	0.0011	0.00072
I.....	0.0042	0.00158	0.00127	0.0009	0.0011	0.00068
J.....	0.00095	0.00053	0.00038	0.00027	0.00026	0.0002
K.....	0.00255	0.00123	0.00088	0.00088	0.00074	0.00064
L.....	0.00246	0.00121	0.00085	0.00079	0.00066	0.00046
M.....	0.00352	0.00158	0.00106	0.00097	0.00052	0.0007
N.....	0.00272	0.00101	0.00076	0.00061	0.00066	0.00044
O.....	0.00343	0.00128	0.00076	0.00028	0.00055	0.00019
P.....	0.00308	0.00119	0.00067	0.00027	0.00041	0.00018
X.....	0.00299	0.00154	0.00109	0.0008	0.00074	0.00059
Reading page						
horizontal ..	0.0088	0.00405	0.00281	0.0022	0.00198	0.0016
Reading page						
45° position	0.00431	0.00273	0.00167	0.00154	0.00117	0.0009

TABLE XII.—INTENSITY SERIES.

Showing some prominent ratios of surface brightness for the different intensities used for the indirect system. An important point of comparison for the purpose of this investigation is the ratios with and without socket extenders.¹⁶

Ratio	800 watts	480 watts	320 watts With socket extenders
Lightest to darkest.....	0.138 / 0.00095 = 145.0	0.0704 / 0.00053 = 133.0	0.0539 / 0.00038 = 142.0
Lightest to test card.....	0.138 / 0.00299 = 46.0	0.0704 / 0.00154 = 45.0	0.0539 / 0.00109 = 49.0
Lightest to reading page.....	0.138 / 0.00431 = 32.0	0.0704 / 0.00273 = 26.0	0.0539 / 0.00167 = 32.0
2nd lightest to darkest.....	0.0715 / 0.00095 = 75.0	0.0385 / 0.00053 = 72.6	0.0252 / 0.00038 = 66.0
2nd lightest to test card.....	0.0715 / 0.00299 = 24.0	0.0385 / 0.00154 = 25.0	0.0252 / 0.00109 = 23.0
2nd lightest to reading page.....	0.0715 / 0.00431 = 16.5	0.0385 / 0.00273 = 14.0	0.0252 / 0.00167 = 15.0
3rd lightest to darkest.....	0.066 / 0.00095 = 66.3	0.0352 / 0.00053 = 66.0	0.0244 / 0.00038 = 64.0
3rd lightest to test card.....	0.066 / 0.00299 = 22.0	0.0352 / 0.00154 = 22.0	0.0244 / 0.00109 = 22.0
3rd lightest to reading page.....	0.066 / 0.00431 = 15.0	0.0352 / 0.00273 = 12.9	0.0244 / 0.00167 = 14.6

200 watts

Ratio	320 watts Without socket extenders	With socket extenders	Without socket extenders
Lightest to darkest.....	0.088 / 0.00027 = 326.0	0.0352 / 0.00026 = 135.0	0.0748 / 0.0002 = 374.0
Lightest to test card.....	0.088 / 0.0008 = 110.0	0.0352 / 0.00074 = 47.0	0.0748 / 0.00059 = 127.0
Lightest to reading page.....	0.088 / 0.00154 = 57.0	0.0352 / 0.00117 = 30.0	0.0748 / 0.0009 = 83.0
2nd lightest to darkest.....	0.0231 / 0.00027 = 85.5	0.0165 / 0.00026 = 63.5	0.0187 / 0.0002 = 93.5
2nd lightest to test card.....	0.0231 / 0.0008 = 28.9	0.0165 / 0.00074 = 22.3	0.0187 / 0.00059 = 31.7
2nd lightest to reading page.....	0.0231 / 0.00154 = 15.0	0.0165 / 0.00117 = 14.0	0.0187 / 0.0009 = 20.8
3rd lightest to darkest.....	0.022 / 0.00027 = 81.5	0.0159 / 0.00026 = 61.0	0.0165 / 0.0002 = 82.5
3rd lightest to test card.....	0.022 / 0.0008 = 27.5	0.0159 / 0.00074 = 21.5	0.0165 / 0.00059 = 28.0
3rd lightest to reading page.....	0.022 / 0.00154 = 14.2	0.0159 / 0.00117 = 13.6	0.0165 / 0.0009 = 18.3

¹⁶ Theoretically considered, the above ratios: lightest to darkest, lightest to test card, lightest to reading page, etc., should be approximately the same for all of the wattages, if the lamps sustain the same relation to the reflector, to the ceiling, etc. A certain unevenness in these ratios will be noted, however, even when socket extenders were used with the 25 and 40-watt lamps. This is no more than is to be expected because socket extenders of only one length could be obtained, and these did not give the same relation of lamp to reflector for the 25 as for the 40-watt lamp, nor the same relation for either of these lamps as was obtained for the 60 and 100-watt lamps. Obviously too the 60-watt lamps did not sustain the same relation to the reflectors as did the 100-watt lamps.

TABLE XIII.—INTENSITY SERIES.

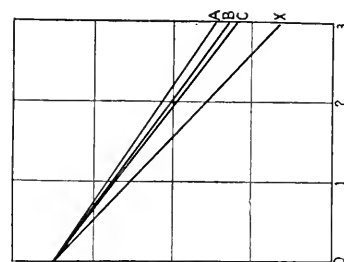
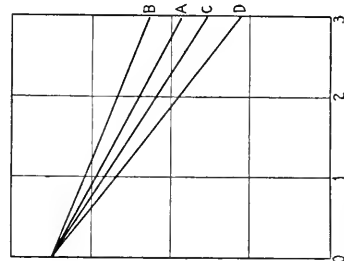
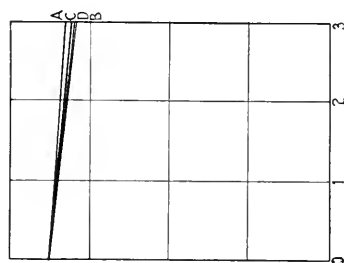
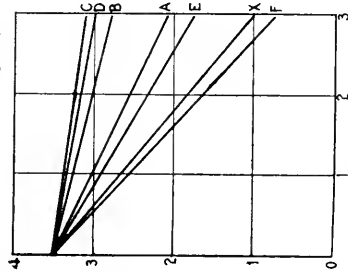
Showing the effect on the efficiency of the eye of varying the intensity of light in an indirect system composed of 8 units, clear tungsten lamps.

Watts	Foot-candles		Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
	Horizon- tal	Verti- cal							
800	5.2	1.36	45° 3.5	9 A.M.	67.5	135	45	3.0	3.5
				12 M.	67.5	132	48	2.75	3.2
480	3.0	0.765	1.97	9 A.M.	65.0	150	30	5.0	3.5
				12 M.	65.0	148	32	4.6	3.22
320	1.7	0.49	1.08	9 A.M.	66.0	140	40	3.5	3.5
				12 M.	66.0	137	43	3.18	3.18
320	1.48	0.407	0.95	9 A.M.	64.0	145	35	4.1	3.5
				12 M.	64.0	138	42	3.29	2.7
200	1.33	0.39	0.87	9 A.M.	64.0	122	58	2.1	3.5
				12 M.	64.0	120	60	2.0	3.3
200	1.16	0.37	0.76	9 A.M.	62.0	149	31	4.8	3.5
				12 M.	62.0	135	45	3.0	2.1

CHART II.—INTENSITY SERIES.

Showing a comparison of the effect on the efficiency of the eye of varying the intensity of light for the four installations of lighting used: the indirect, semi-indirect, and direct systems, 8 lamps; and the direct system, 16 lamps.¹⁷

Lighting system: Semi-indirect				Lighting system: Indirect				Lighting system: Direct (8 lamps)				Lighting system: Direct (16 lamps)			
Foot-candles				Foot-candles				Foot-candles				Foot-candles			
Watts	Volts	Hori- zontal	Verti- cal	Watts	Volts	Hori- zontal	Verti- cal	Watts	Volts	Hori- zontal	Verti- cal	Watts	Volts	Hori- zontal	Verti- cal
A 200	107	1.6	0.45	A 200	107	1.33	0.39	A 120	107	0.64	0.32	A 240	107	1.23	0.54
B 200	110	1.72	0.484	B 320	107	1.7	0.49	B 200	107	1.16	0.45	B 365	107	1.6	0.6
C 320	107	2.2	0.58	C 480	107	3.0	0.765	C 320	107	1.97	0.65	C 400	107	1.86	0.8
D 320	110	2.31	0.62	D 800	107	5.2	1.36	D 480	107	2.6	1.02	X 880	107	4.2	1.41
E 480	107	3.3	0.94												
F 800	107	6.8	1.82												
X 760	107	5.8	1.45												

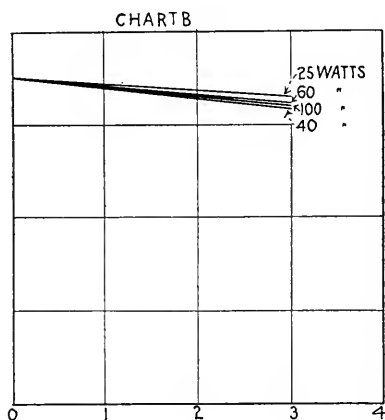
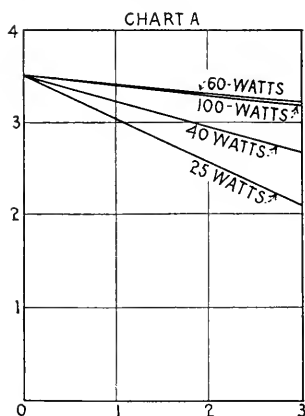


¹⁷ For a full specification of the illumination effects, brightness and illumination measurements, brightness ratios, etc., produced by the direct and semi-indirect systems for the different wattages, see the previous paper (op. cit., pp. 428-441).

A graphic representation of the results for the indirect system with socket extenders is given in Chart II. In this chart loss of efficiency is plotted against time of work in the manner described in the preceding section. For the sake of comparison results are shown also on this chart for the direct and semi-indirect systems. A graphic representation has further been made of the results for the indirect system with and without socket extenders. This is shown in Chart III.

CHART III. -INTENSITY SERIES.

Showing the effect on loss of efficiency of changing the height of the light source in the reflector of the indirect lighting fixtures. The effect on surface brightness is primarily to change the area and surface brilliancy of the spot of light thrown on the ceiling. Chart A shows the results when height of source in the reflector is changed; Chart B, the results when the height is kept approximately constant.



EYE SHADE SERIES.

This series of experiments has been conducted for the following reasons. (1) In general two methods are used to protect the eye from the source of light, eye shades and lamp shades. It is desirable to know whether the eye is protected equally well by both; and if the eye shade can be substituted for the lamp shade, what type of shade would best serve the purpose. (2) And the statement has been made to us many times that with an eye shade the three systems of artificial lighting we have used should give equally good results; and results, moreover, as good

as those given by the indirect system without an eye shade. There are in general two classes of eye shades, the translucent and opaque. Up to this time we have confined our work to the opaque shade. So far as we know it is customary to make the opaque shade with a dark lining. This kind of lining is employed probably because of some notion that it is restful to the eye to darken as much of the field of vision as is possible.¹⁸

The tests were begun with the opaque shade with the dark lining. What we found as the result of these tests was somewhat in contradiction to the predictions that had been made. The shade did give pretty nearly the same results for the three systems; but it did this, contrary to prediction, by improving the direct and semi-indirect systems and making worse by almost an equal amount the indirect system. That is, protected by the opaque shade, the eye lost in efficiency for the three systems by an amount somewhere near the mean of the losses experienced by it for the three systems without a shade. Nor is this result surprising when one reflects upon the conditions imposed upon the eye by an opaque shade with a dark lining. While it protects the eye from the sources of light, such a shade does not by any means eliminate harmful brightness differences in the field of vision. It in fact creates for the eye a very unnatural brightness relation, *i. e.*, it renders the whole upper half of the field of vision dark in sharp contrast with the brightly lighted lower half. The direct effect of this is a strong brightness induction (physiological) over the lower half of the field of vision which manifests itself to the observer by causing glare in surfaces that have no glare, and by increasing the glare in surfaces in which glare is already present. This, it is scarcely necessary to point out, operates against the discrimination of detail and puts the eye under strain to see its objects clearly. Moreover, the unusual and strongly irregular character of the image formed on the retina probably also sets up a warfare in the incentives given to the muscles which adjust the eye. That is, the upper half of the field of vision is dark and presents no detail. The effect of this is probably to exert a tendency to cause the muscular relax-

¹⁸ Another popular view might be, so far as protection to the eye is concerned, to regard the opaque eye shade as the analogue of the opaque or perhaps the indirect lamp reflector and the translucent shade as the analogue of the semi-indirect reflector.

ation characteristic of the darkened field of vision. The lower half of the field is light and filled with detail. The incentive here is towards the best possible adjustment of the eye for the discrimination of detail in the objects viewed, while the rim of the shade, the sharply marked boundary between the dark and light halves of the field of vision and much nearer to the eye than the objects viewed,¹⁹ serves as a constant and consciously annoying distraction to fixation and accommodation. These complex and somewhat contradictory impulses given to the muscles of the eye might very well, and doubtless do cause an excessive and unnatural loss of energy and efficiency in case of the prolonged adjustment of the eye needed for a period of work.

Early in the course of the tests it occurred to us that we might render the brightness distribution in the field of view presented to the eye wearing a shade more natural, and thereby improve the effect of the shade on the eye, by employing a white instead of a dark lining. By using a matt white paper²⁰ with a reflection coefficient of about 75 per cent. for this lining, the following effects were produced. The two halves of the field of vision were rendered much more nearly of equal brightness; the glare in the lower half of the field of vision was very noticeably lessened and the discrimination of detail was correspondingly improved; the upper half of the field of view no longer tended to give to the eye the reflexes of the darkened field of vision; and the rim of the shade did not stand out nearly so distinctly in the field of view to distract accommodation and fixation. The results of the test for loss of efficiency show, moreover, that our surmise with regard to the effect of this change on the eye was correct. The action of the white lining was greatly to improve the ability of the eye to maintain its efficiency for a period of work. As good results were not gotten, however, with the shade for any of the systems as were given by the indirect system without the shade. Since there was a still greater evenness of surface brightness in the field of view in case of the indirect system with the eye shade than without, the question arises why

¹⁹ This rim is about three inches in front of the observer's eye when the shade is in position.

²⁰ Hering standard white paper was used for this lining. The reflection coefficient of the dark lining was about 6-8 per cent.

at least as good results were not obtained with the shade as without. The answer, we believe, is to be found in terms of the distraction to fixation and accommodation caused by the eye shade even when a light lining was used. For the effect of a shade on the eye even when the most favorable lining is employed is that of a constantly present distracting object with its lower margin not far removed from the center of the field of vision, and much nearer to the eye than are the objects which the observer is called upon to discriminate. It will be noticed also in Table XVII that the results were never so good for either kind of shade for the direct and semi-indirect systems as for the indirect. Since the evenness of surface brightness in the field of view was not very different for the three systems in both cases, this again probably indicates that the evenness of surface brightness is not the only one of the distribution factors that has to be taken into account in studying the effect of different conditions of lighting on the eye.

These tests were made for the same installations that were used in the distribution series. Since the use of the eye shade did not affect the illumination of the room the reader is referred for the illumination measurements to the tables of the distribution series. The distribution of surface brightness in the field of vision, however, was strongly affected. New measurements were made, therefore, of the brightness of the prominent surfaces in the field of vision. The tests were taken at Position I, see Fig. 1, p. 452a. The prominent surfaces in the observer's field of vision working in this position were J, K, and L (see Fig. 4, p. 452b); the top of the table carrying test and recording apparatus, immediately in front of the observer and below the level of his eyes; the test card; the reading page in the 45 deg. position; and the white and dark lining of the eye shade as seen by the observer when the shade was in position over his eyes. The measurements of the brightness of the lining of the eye shades as seen by the observer when the shades were in position were made as follows. A surface in front of the observer was made to match in brightness the lining of the shade as it was seen by him. The brightness of this surface was then measured by the method described on page 452. In procuring the match between the comparison surface and

the lining of the shade the series of Hering matt gray papers was employed. This series consists of 50 shades ranging from a white with a reflection coefficient of 75 per cent. to black. Sheets of these differing in brightness were placed in a vertical position at a given distance in front of the observer until an approximate match was made with the lining of the shade. The gradations needed to get the final match were secured by moving the surface to and from the observer and by tilting it at different angles with the line of sight. The former adjustment carried it into parts of the room having different intensities of illumination and the latter turned it so as to receive a greater or less amount of light. In making the brightness measurements, care was taken to have the receiving surface of the photometer arm normal at its central point to the line of sight taken by the observer when the match was made. The results of these measurements are shown in Table XIV. In Table XV are given some of the prominent ratios of surface brightness in the field of vision for the shade with the dark lining; and in Table XVI, some of the prominent ratios for the shade with the white lining. In Table XVII are shown the results for the test for loss of efficiency for the shade with the dark lining; and in Table XVIII for the shade with the white lining. For purposes of comparison the results of the three systems without a shade are repeated. These are given in Table XIX. A graphic representation results of all three tables is given in Chart IV.

TABLE XIV.—EYE SHADE SERIES.

Showing the brightness measurements in candlepower per square inch for the various surfaces in the field of vision for the direct, semi-indirect and indirect systems used when the eyes were shielded in turn by an opaque eye shade with a dark lining, and an opaque eye shade with a white lining.

Surface measured	Direct system	Semi-indirect system	Indirect system
J.....	0.0014	0.001	0.00095
K.....	0.0063	0.0046	0.00255
L.....	0.0042	0.0027	0.00246
Table	0.0029	0.00255	0.00233
Test card.....	0.00308	0.003	0.00299
Reading page 45° position.....	0.004	0.0039	0.00431
White lining of eye shade.....	0.00197	0.00204	0.00207
Dark lining of eye shade.....	0.000091	0.00011	0.000126

TABLE XV.—EYE SHADE SERIES.

Showing some prominent ratios of surface brightness for the direct, semi-indirect, and indirect systems used when the eyes were shielded by an opaque eye shade with a dark lining.

Ratio	Direct system	Semi-indirect system	Indirect system
Lightest to darkest.....	0.0063/0.000091 = 69.2	0.0046/0.00011 = 42.0	0.00431/0.000126 = 34.2
Lightest to test card.....	0.0063/0.00308 = 2.04	0.0046/0.003 = 1.53	0.00431/0.00299 = 1.5
Lightest to reading page.....	0.0063/0.004 = 1.56	0.0046/0.0039 = 1.2	0.00431/0.00431 = 1.0
Lightest to lining of eye shade.....	0.0063/0.000091 = 69.2	0.0046/0.00011 = 42.0	0.00431/0.000126 = 34.2

TABLE XVI.—EYE SHADE SERIES.

Showing some prominent ratios of surface brightness for the direct, semi-indirect, and indirect systems used when the eyes were shielded by an opaque eye shade with a white lining.

Ratio	Direct system	Semi-indirect system	Indirect system
Lightest to darkest.....	0.0063/0.0014 = 3.9	0.0046/0.001 = 4.6	0.00431/0.00095 = 4.5
Lightest to test card.....	0.0063/0.00308 = 2.04	0.0046/0.003 = 1.53	0.00431/0.00299 = 1.0
Lightest to reading page.....	0.0063/0.004 = 1.56	0.0046/0.0039 = 1.2	0.00431/0.00431 = 1.0
Lightest to lining of eye shade.....	0.0063/0.00197 = 3.2	0.0046/0.00204 = 2.25	0.00431/0.00207 = 2.5

TABLE XVII.—EYE SHADE SERIES.

Showing the eye's loss in efficiency as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed. (With opaque eye shade with dark lining.)

Lighting system	Watts	Foot-candles		Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
		Horiz-ontal	Verti-cal							
Indirect	800	5.2	1.36	45° 3.5	80.0 80.0	68 68	143 130	37 50	3.86 2.6	3.5 2.34
Semi-indirect	760	5.8	1.45	4.0	80.0 12 M.	68 68	126 110	54 70	2.33 1.55	3.5 2.33
Direct	880	4.2	1.41	2.6	79.0 12 M.	67 67	139 124	41 56	3.39 2.21	3.5 2.27

TABLE XVIII.—EYE SHADE SERIES.

Showing the eye's loss in efficiency as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed. (With opaque eye shade with white lining.)

Lighting system	Watts	Foot-candles		Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
		Horiz-ontal	Verti-cal							
Indirect	800	5.2	1.36	45° 3.5	85.0 12 M.	68 68	118 115	62 65	1.9 1.77	3.5 3.18
Semi-indirect	760	5.8	1.45	4.0	85.0 12 M.	68 68	128 124	52 56	2.46 2.21	3.5 3.13
Direct	880	4.2	1.41	2.6	85.0 12 M.	70 70	105 100	75 80	1.4 1.25	3.5 3.07

TABLE XIX.—EYE-SHADE SERIES.

Showing the eye's loss in efficiency as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed (No eye shade.)

Lighting system	Watts	Foot-candles			Time	Maximal distance at which test object can be seen clear
		Horizontal	Vertical	45°		
Indirect	800	5.2	1.36	3.5	9 A.M.	84.5
					12 M.	84.5
Semi-indirect	760	5.8	1.45	4.0	9 A.M.	80.5
					12 M.	79.5
Direct	880	4.2	1.41	2.6	9 A.M.	81.0
					12 M.	78.0
		Work- ing dis- tance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
Indirect	67.5		135	45	3.00	3.5
	67.5		132	48	2.75	3.2
Semi-indirect	68.5		142	38	3.73	3.5
	68.5		92	88	1.64	0.97
Direct	68.0		139	41	3.39	3.5
	68.0		771	109	0.69	0.671

As yet we have not determined the effect of translucent shades on the eye. In attempting to deal in a general way with this class of shades we have the same type of difficulty to face that we have in case of the semi-indirect reflector. That is, we may have shades varying from transparent to opaque, and sharing in the merits and demerits of each extreme. Our judgment would be, however, that it would be very difficult to get a translucent shade that would give as good results as an opaque shade with a light lining; for the translucent shade when made sufficiently opaque to give the needed reduction to the image of the source will darken too much the upper half of the field of vision and thereby simulate too much the condition given by the opaque shade with the dark lining to give the best results for comfortable and efficient seeing. Moreover, from the results that have already been obtained with the opaque shade and from the principles it seems fair to infer from these results, it seems very probable to us that as good effects for seeing should not be expected from the use of

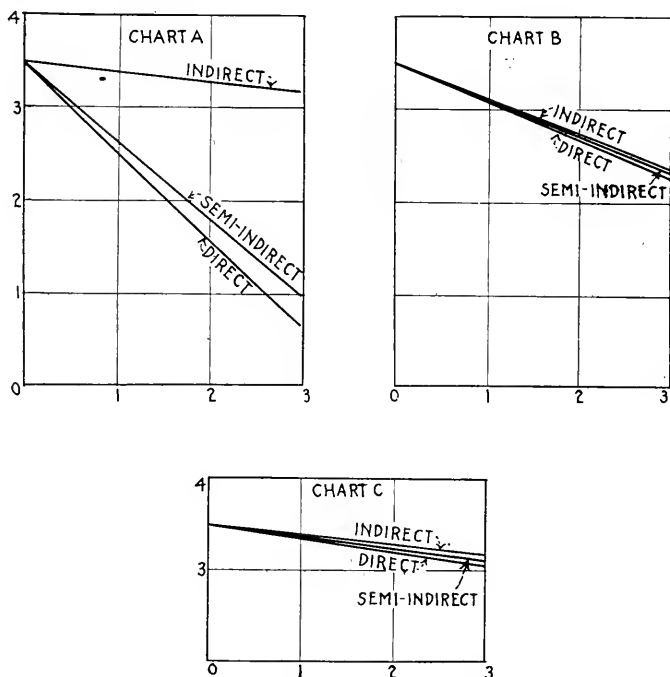
any kind of eye shade as may be gotten from lamp-shades. That is, if we are to secure the best results for seeing, the shade should be put on the lamp, not on the eye.

THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

The object of these experiments was to find out whether the

CHART IV.—EYE SHADE SERIES.

Showing the effect on loss of efficiency of opaque eye shades with dark and with white lining for the installations direct, semi-indirect, and indirect with the same intensity of light at the point of work. Chart A shows results without shade; Chart B, with shade having dark lining; Chart C with shade having white lining.



difference in the angle at which the light falls on the work produces an effect on the eye that can be detected by the test we have used for loss of efficiency. For the purpose of this preliminary investigation it was decided to make the general illumination of the room such as to cause the eye little loss of effi-

ciency as the result of the period of work; and to add to that at the point of work a component of light which was less diffuse in order that the amount of light entering the eye would be more dependent upon the angle at which the reading page was held.

The general illumination was obtained from the indirect system used in the work of the preceding sections with lamps totalling 800 watts. The less diffuse component at the point of work was obtained from a 60-watt lamp with a porcelain reflector of the desk lamp type. This lamp was turned into the horizontal position and was placed behind the observer and to the left so that the light came over the left shoulder. When in the position for which the test was taken the tip of the lamp was slightly above the level of the observer's eye, at a distance of 1 meter from the left eye.

The illumination and brightness measurements for the test room illuminated by the indirect system, 800 watts, are given on pp. 469 and 471. These measurements were not greatly changed by the addition of the 60-watt lamp behind the observer. Because of the presence of this lamp, however, the following measurements were added to those given on pp. 469 and 471: the horizontal, vertical, and 45 deg. components of light at the point of work; the brightness of the test card in place for the test; and the brightness of the reading page when held respectively in the positions which gave the least and the greatest amounts of specular reflection. The illumination measurements at the point of work are given in Table XX. The brightness of the test card was 0.00365 cp. per sq. in.; of the reading page in the position that gave the least amount of specular reflection, 0.0059 cp. per sq. in.; and in the position that gave the greatest amount of specular reflection, 0.0077 cp. per sq. in. A mirror surface was used as an aid in locating the position of least and greatest specular reflection. The results of the test for three hours of work done with the reading page in these two positions are also given in Table XX. A graphic representation of the results of this table is shown in Chart V.

THE EFFECT OF DIFFERENT CONDITIONS OF LIGHTING ON THE FIXATION MUSCLES OF THE EYE.

The test we have employed thus far in the conduct of our

work is one designed to show the effect of different conditions of lighting on the ability of the eye to hold its efficiency for clear seeing for a period of three minutes. In itself this test is not

TABLE XX.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

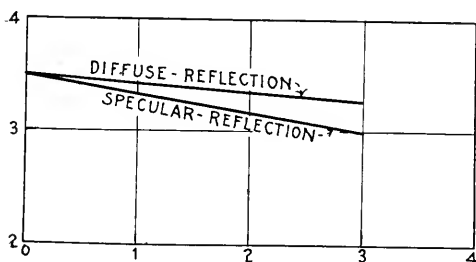
Showing the effect on loss of efficiency of the angle at which the light falls on the work.

Kind of reflection from reading page during work period	Foot-candles at test-card			Time	Maximal distance at which test object can be seen clear
	Hori- zontal	Verti- cal	45°		
Diffuse	5.3	1.84	3.9	9 A.M.	89
				12 M.	89
Specular	5.3	1.84	3.9	9 A.M.	89
				12 M.	89
				Total time clear, ÷ total time blurred	Ratios reduced to common standard
Diffuse	73	139	41	3.39	3.5
	73	137	43	3.18	3.27
Specular	73	137	43	3.18	3.5
	73	132	48	2.73	3.0

analytical in principle. The results, as is stated above, are expressed in terms of an aggregate loss of function. The contributive factors may be inferred from the nature of the test, but

CHART V.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

Showing the effect on loss of efficiency of the angle at which the light falls on the work.



the test is not in itself designed to separate them out. And indeed it is a question whether any practical good can accrue to the practise of lighting from a knowledge of just what part of

the visual apparatus it is that falls off in function as the result of an unfavorable condition of lighting. Obviously the chief need is to find out what are the conditions that cause the eye to lose its ability to see clearly and to avoid these conditions in planning and installing a lighting system. From the beginning we have had in mind, however, an analysis of effect. Our tests for the sensitivity of the retina showed, for example, that very little, if any, of the difference in results we have gotten for the four types of lighting we have employed can be ascribed to a loss in the efficiency of the retina, or the light sensitive part of the visual apparatus. Three sets of factors are involved in clear seeing: (1) the sensitivity of the eye to colored and white light; (2) the ability to make fine space discriminations which is in part dependent upon our third factor; and (3) accurate fixation and accommodation. Both fixation and accommodation are the result of muscular action. When the muscles lose in tone because of excessive use or by sharing in a general condition or state of the body, the eye loses correspondingly in its power to sustain clear seeing. If, for example, the muscles of accommodation have fallen off in efficiency the lens is no longer held in the adjustment needed to bring the light to a sharp focus on the retina and loss of detail and blurring result; or, if it be the fixation muscles that have suffered the loss, the eyes cannot be continuously held in such a position that the images of the object viewed fall symmetrically on the fovea of each. When this latter condition is present loss of detail results from two causes. (1) The fovea and region immediately surrounding it are the most highly developed parts of the retina and the best fitted for the light and space discriminations needed for clear seeing. Moreover, the refracting media of the eye give the clearest images when the axis of the cone of rays from the object viewed deviates as little as possible, consistent with the mechanism of the eye, from the optic axis. And (2) if the images in the two eyes do not fall more or less symmetrically upon the fovea of each they are not accurately combined into one, and blurring and loss of detail results from the doubling of the objects seen. It is our purpose as fast as possible to isolate the effect of the three systems of lighting we have used on each of the above named factors. In

the work of the present section the effect of these systems on the fixation muscles has been studied.

The doubling of the image seen when the fixation muscles lose their power of co-ordinated action furnishes us with our clue for a test for the loss of efficiency of these muscles. That is, just as blurring and the loss of ability to discriminate detail is taken as the criterion of the loss of acuity of vision, so will the doubling of the image seen be taken as our index of the loss of the co-ordinated action of the fixation muscles. If one were to stare continuously for an interval of time with natural vision at a simple test object, as, for example, a vertical line, doubling might be detected especially if there had been protracted strain or considerable loss of power to co-ordinate. For the purpose of our work, however, greater sensitivity than this would be needed. Obviously sensitivity can be added by putting the eyes under strain to combine their images. When this is done, even when the muscles are fresh, if the object is looked at or fixated for an interval of time it will be seen alternately as one and as two. The proportion or ratio of the time seen as one to the time seen as two can be regulated by the amount of initial strain under which the eyes are put to combine their images. The regulation of this ratio is empirical and of importance; for as is the case with the test for loss of efficiency for clear seeing, the sensitivity of the test depends to a considerable extent upon the initial value that is given to this ratio. The eyes may be put under strain to combine their images by interposing between them and the object viewed weak prisms and so adjusting them and regulating the distance of the object from the eye that with the maximum of effort to see it as one it is seen alternately as one and as two in the proportion desired.²¹ This result can be accom-

²¹ It would seem that the above principle might be utilized to advantage by the ophthalmologist in testing the extrinsic muscles of the eye. The abduction and adduction tests, for example, determine only what the muscles are able to do by momentary effort. Obviously, however, it is not what the muscles are able to do by a momentary effort or jerk that measures their ability to hold the eyes continuously adjusted for work. It is rather their endurance or what they are able to accomplish in an interval of time. An expression may be had for this either for the eyes conjointly or separately by the method described above. That is, the prisms may be put in front of either one or both eyes and the ratio be determined of the time the object is seen as one or as two for whatever interval of time the operator may select. Similarly, it seems to the writers that the time element might be introduced to ad-

(Continued on next page.)

plished still more conveniently, however, by using an adaptation of the Brewster stereoscope. In this case a stereograph consisting of two vertical lines exactly alike may be used as the test object. In the stereograph employed in our test the vertical lines were 2.5 cm. long and were printed on the card 4.5 cm. apart or at 2.25 cm. from the center of the card. When this was put in a sliding carrier and was made to approach the eyes, a position was reached at which with the maximum of effort the observer was no longer able to see the two vertical lines as one. They were seen alternately as one and as two. In making the test the hood was removed from the stereoscope so that the eyes were fully exposed to the conditions of illumination that were being tested. The stereoscope was mounted in front of the eyes of the observer in position at the point of work. The distance of the carrier containing the test object from the observer's eyes was adjusted until the proper ratio of time seen as one and time seen as two was obtained. Having determined this position a record was made of the time seen as one and the time seen as two for three minutes at the beginning and the close of work. The ratio of the sum of these intervals may in either case be taken as a measure at that time of the power of the fixation muscles to act in co-ordination for three minutes of continuous effort; and the decrease in this ratio from the beginning to the close of work may be taken as a measure of the loss in that power, sustained as the result of work. In making this test the same recording apparatus was used as was employed in the test for loss of efficiency for clear seeing. That is, the record was traced on a kymograph by means of an electro-magnetic marker and a

vantage into the visual acuity test used by the ophthalmologist when the cycloplegic is not employed or in cases of post-cycloplegic refraction. Is it, for example, enough to know that the eye has 20/20 acuity or can discriminate a certain standard visual angle by momentary effort? Would it not give a more complete representation of the functional condition of the eye to know what it can discriminate clearly through an interval of time; or better still perhaps, for what proportion of an interval of time it can discriminate a certain detail or standard visual angle clearly? For example, just as a fatigued eye may for the moment under the spur of the test overcome the functional results of fatigue, so might small errors of refraction be overcome for the moment by muscular effort, especially in the cases in which the muscles of the eye are unusually strong. But just as the fatigued muscle can not do this through an interval of time, so it would seem that a residual error of refraction might not be so easily masked through an interval of time by means of muscular effort. In short, this form of test is suggested as affording possibly a closer approximation to the conditions and demands imposed upon the eye during a period of work than is afforded by the acuity test based upon the momentary judgment.

telegraph key, and a time line was run beneath the record by means of a Jacquet chronograph registering seconds.

The test for the effect on the fixation muscles of a period of work was made under the same installations, conditions of work, and with the same observers that were used in the distribution series. The test, however, was made at only one of the positions used in that series, namely, the position at which the greatest loss of efficiency was obtained. (See Position I, Fig. 1, p. 452a.) At this point, it will be remembered, six of the lighting

TABLE XXI.—FIXATION MUSCLES SERIES.

Showing the loss of efficiency of the fixation muscles as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed.

Lighting system	Watts	Foot-candles			Time	Distance at which test object is normally seen single
		Hori- zon- tal	Verti- cal	45°		
Indirect	800	4.2	0.99	2.5	9 A.M.	18
					12 M.	18
Semi-indirect	760	4.8	0.98	2.6	9 A.M.	18
					12 M.	18
Direct	880	3.9	1.0	1.99	9 A.M.	18
					12 M.	18
		Work- ing dis- tance	Total time single	Total time double	Total time single ÷ total time double	Ratios reduced to common standard
Indirect		22	142	38	3.7	3.5
		22	140	40	3.5	3.31
Semi-indirect		22	141	39	3.6	3.5
		22	138	42	3.28	3.24
Direct		20	153	27	5.66	3.5
		20	151	29	5.21	3.21

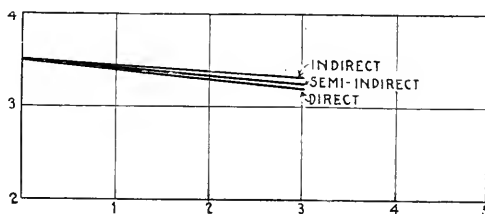
units were in the field of view. The specification of the lighting effects produced by these installations are given on pp. 452a-459. Nothing need be added at this point to these specifications but the brightness of the stereograph or the test object in position for the three systems of lighting, and the illumination measurements at the test card. The brightness measurements are as follows. The brightness of the card, corrected for the absorption of the prisms of the stereoscope was for the direct system 0.00172 cp. per sq. in.; for the semi-indirect system,

0.00163 cp. per sq. in.; and for the indirect system, 0.00167 cp. per sq. in. New illumination measurements were needed at the test card because the card had to be moved closer to the eyes than was the case in the tests for loss of efficiency for clear seeing, which brought it into a region of different illumination. These measurements are given in Table XXI. The results of our tests for loss of efficiency of the fixation muscles for the three systems of lighting are given also in this table. These results show (a) that very little loss of co-ordination is suffered by the fixation muscles as the result of three hours of work under the systems selected; and (b) that there is very little difference in

CHART VI.—FIXATION MUSCLE SERIES.

Showing the loss of efficiency of the fixation muscles as the result of 3 hours of work under the direct, semi-indirect, and indirect systems of lighting employed.

Lighting system	Watts	Foot-candles		
		Horizontal	Vertical	45°
Indirect	800	4.2	0.99	2.5
Semi-indirect ..	760	4.8	0.98	2.6
Direct	880	3.9	1.0	1.99



the effect for the three systems. Since there is no reason for thinking that the test has not as great sensitivity as the test for loss of efficiency for clear seeing, and since the same observers, conditions of lighting and working were used as in the former tests, it does not seem to us at this time that the loss of efficiency for clear seeing that is sustained under these conditions, shown by the former tests, can be ascribed to any great extent to an effect on the muscles of fixation. In a later report experiments will be described in which the effect on the muscles of accommodation has been studied.

A graphic representation of the results of Table XXI is shown in Chart VI.

THE EFFECT OF MOTION PICTURES ON THE EFFICIENCY
OF THE EYE.

The belief that motion pictures subject the eyes to undue strain is too prevalent to need more than mention in passing. All are familiar with the conditions,—the initially dark-adapted and highly sensitized eye, the comparatively brilliant screen with its dark surrounding field, the flickering light, and the shifting and very often unsteady pictures. We have already seen that differences in surface brightness of considerable magnitude in the field of vision cause loss of efficiency and produce discomfort, and we have discussed the causes for these effects. We have nothing further to add to that discussion here. We are, however, facing for the first time in our work the question of the effect upon the eye of a flickering light and lack of steadiness in the object viewed. The following reason is suggested why a flickering or unsteady picture may cause loss of efficiency. The eye is so constituted that when its images lose in clearness or distinctness it is incited to a muscular readjustment to bring about the clearness needed. Ordinarily in seeing, the conditions for loss in clearness come about primarily through the difference in the distance or direction from the eye of the objects which are successively viewed. In motion pictures, however, the changing clearness of the objects viewed is not due to any change in their distance or direction from the eye; nor to anything in fact which the readjustment of the eye can remedy to any considerable degree. The effort expended, therefore, is of little avail for seeing, if, indeed, the new setting of the parts is not a detriment to clear seeing and a condition which in turn must be corrected. This should, and doubtless does, lead to muscular strain and loss of efficiency. It was decided, therefore, to make an explorative investigation to determine whether there is an effect of motion pictures on the eye which can be detected by our test for loss of efficiency. The tests were conducted in a local theater, selected primarily because of the favorable conditions that prevailed. The definition at the screen was good and the pictures were unusually steady and free from flicker. The conditions were, we think, fairly representative of what is found in the better class of motion picture houses.

The tests were taken immediately before and after two hours of observation of the pictures. During the exhibition the observer sat directly in front of the center of the screen. The observation was made at successive times at three distances from the screen,—in the front, middle, and the back of the house. These positions were respectively 25, 48, and 71 ft. (7.62, 14.6, and 21.6 m.) from the screen. The room in which the pictures were shown was 78 ft. (23.7 m.) long and 48 ft. (14.6 m.) wide. The tests were taken in a room 14 ft. (4.2 m.) long, 9 ft. (2.74 m.) wide, 11 ft. (3.35 m.) high, adjoining the stage. The walls and ceiling of this room were of rough plaster, painted a flat white. When taking the test the observer sat facing one of the side walls of the room, 1.5 m. distant. The room was lighted for the purpose of the test by one 100-watt and one 60-watt clear tungsten lamp suspended behind and slightly to the right of the observer when in position for the test, at about 2 ft. (0.6 m.) above the level of his eyes. The source of light was thus entirely out of the field of view and the light fell evenly and without shadow on the test card and the wall in front of the observer. At the point of the test card, the illumination measured with the receiving test plate of the photometer in the horizontal plane was 1.3 foot-candles; in the vertical plane, 1.9 foot-candles; and in the 45 deg. plane, 2.3 foot-candles. The surface brightness of the test card was 0.003256 cp. per sq. in., and that of the wall directly behind the card was 0.002288 cp. per sq. in. The distribution of surface brightness on the wall which the observer faced was very even. At the point of maximum brightness to the right of the observer, as nearly as that point could be located, the brilliancy was 0.00308 cp. per sq. in.; and to the left of the observer, 0.002024 cp. per sq. in.

In order that there might be no intermission between the pictures for changing the films, two projection machines were used. The following is the specification of the apparatus employed as given by the operator.

Type of machine, Powers 6—A Projector.

Lens equipment, 1 pair pearl white condensers, 6½ in. F. L.

1 Bausch and Lomb objective combination,
4¾ in. E. F.

Lamp, 1 10,000-cp. adjustable arc.

Carbons, $\frac{5}{8}$ in. cored bio's.

Current, 22 volt a. c. through Halberg transformer.

Line current, 28-30 amperes.

Arc voltage, 45-50 volts.

Length of throw or distance from objective to screen, 72 ft.
(21.9 m.)

Screen, sheet muslin sized and coated with flat white alabastine.

Speed of film through machine, 66 ft. 8 in. (20.3 m.) per min.

Number of pictures per 1 ft. (0.3 m.) of film, 16.

Size of picture on film, $\frac{3}{4}$ in. (1.9 cm.) high by $\frac{15}{16}$ in. (2.38 cm.) wide.

Size of picture on screen, 11 ft. (3.35 m.) high by 14 ft. (4.26 m.) wide.

Approximate brightness of screen with film removed from projector, 3.47 cp. per sq. in.

Exceptional steadiness, it may be said, is given to the movement of the film and, therefore, to the picture in this type of projector by the special type of intermittent movement that is employed. Details of this movement need not be given here. As has already been stated, our reason for making the test in this particular theater was the comparative steadiness of the pictures and the comparative freedom from flicker, that was obtained.

The results of the tests are shown in Table XXII. Quite a great deal of loss of efficiency is shown as the result of two hours of observation. The nearer the observer was to the screen, the greater was this loss found to be. The loss, however, so far as we can tell, is no greater than is caused by steady work under the direct and semi-indirect installations of lighting used in our distribution series. Unfortunately, we have not for the purposes of comparison, results for the same observer for the same length of time of exposure for the two sets of condition. The loss for observer R for two hours observation of the motion pictures was not nearly so great as for three hours of reading from good print and paper, under the direct and semi-indirect systems of lighting. But comparing the results for observer G for two hours of reading from the same type and paper with those for observer R for two hours observation of the pictures the

loss seems to be about the same. That is, our results indicate that while the eyes are strained a great deal by the observation

TABLE XXII.—MOTION PICTURE SERIES.

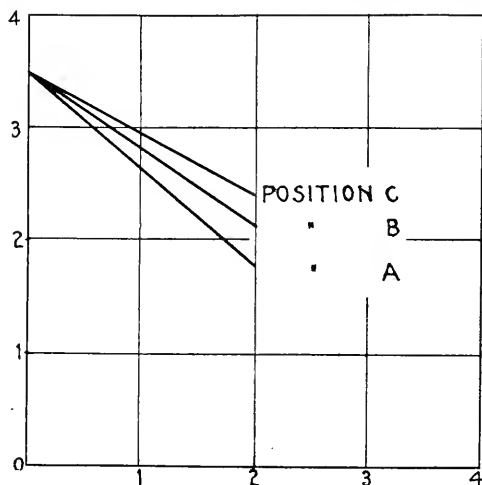
Showing the loss of efficiency of the eye caused by two hours' observation of motion pictures.

Position	Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard
25 ft. (7.62 m.) from projection screen..	8 P.M.	86.2	70.5	123	57	2.14	3.5
	10 P.M.	86.1	70.5	95	85	1.12	1.79
48 ft. (14.63 m.) from projection screen..	8 P.M.	85.8	71.0	128	52	2.46	3.5
	10 P.M.	85.6	71.0	108	72	1.5	2.13
71 ft. (21.64 m.) from projection screen..	8 P.M.	86.0	69.0	137	43	3.19	3.5
	10 P.M.	86.0	69.0	124	56	2.2	2.42

CHART VII. MOTION PICTURE SERIES.

Showing the loss of efficiency of the eye caused by two hours observation of motion pictures.

Position A 25 ft. from projection screen
 Position B 48 ft. from projection screen
 Position C 71 ft. from projection screen



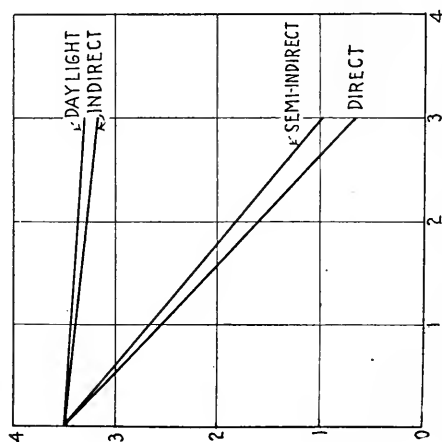
of moving pictures, even in the better moving picture houses, they are damaged little more by that in all probability than they are by

CHART VIII.

DISTRIBUTION SERIES (OBSERVER R.)

Showing the loss of efficiency of the eye as the result of three hours of reading under the systems of direct, semi-indirect, and indirect lighting used, and daylight.

Lighting system	Foot-candles		45°
	Watts	Horizontal Vertical	
Daylight	—	5.5	1.32 4.2
Indirect	800	5.2	1.36 3.5
Semi-indirect .	760	5.8	1.45 4.0
Direct	880	4.2	1.41 2.6

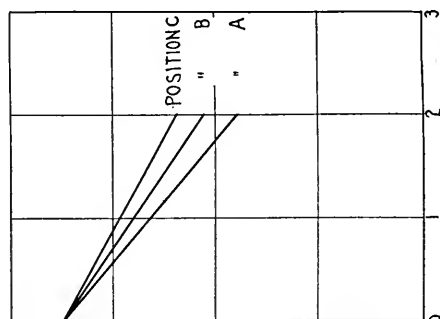


MOTION PICTURE SERIES

(OBSERVER R.)

Showing the loss of efficiency of the eye caused by two hours observation of motion pictures.

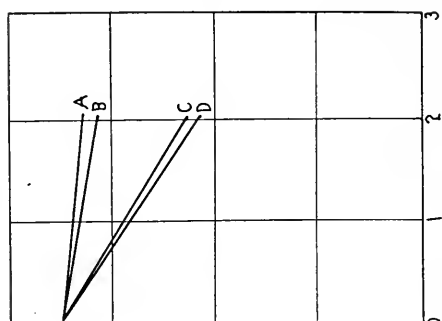
Position A, 25 ft. from projection screen
 Position B, 48 ft. from projection screen
 Position C, 71 ft. from projection screen



DISTRIBUTION SERIES (OBSERVER G.)

Showing the loss of efficiency of the eye as the result of two hours reading under the systems of direct, semi-indirect, and indirect lighting used, and daylight.

Lighting system	Foot-candles		45°
	Watts	Hor. Ver.	
Daylight	—	5.5	1.32 4.2
Indirect	800	107	5.2 1.36 3.5
Semi-indirect	760	107	5.8 1.45 4.0
Direct	880	107	4.2 1.41 2.6



reading steadily the same length of time under the greater part of the lighting that is now in actual use.

A graphic representation of the results of Table XXII is given in Chart VII. For the sake of comparing the effect of motion pictures on the eyes with the effect of reading steadily under the direct, semi-indirect, and indirect systems of lighting we have employed, Chart VIII has been prepared.

THE TENDENCY OF DIFFERENT LIGHTING CONDITIONS TO
PRODUCE DISCOMFORT, AND A COMPARISON OF THE
TENDENCY OF THESE CONDITIONS TO CAUSE
LOSS OF EFFICIENCY AND TO PRODUCE
DISCOMFORT.

In the former papers we have held that the general level or scale of efficiency of the fresh eye, loss of efficiency as the result of work, and the tendency to produce discomfort are all separate aspects of the problem of lighting in its relation to the eye, and that our knowledge of each must be obtained by different methods of investigation. A correlation between these three moments is doubtless possible, but that correlation should be founded upon the results of careful investigation; it should not be assumed. It is our purpose in this section of the paper to show the relative tendency of the different conditions of lighting we have used to produce discomfort, and to make a rough comparison of each condition to cause loss of efficiency and to produce discomfort. Any comparative study of the conditions producing discomfort necessitates a means of estimating discomfort. It is obvious that the core of the experience of discomfort is either a sensation or a complex of sensations. As such it should have a limen or threshold just as other sensations have; and just as we are able in general to estimate sensitivity in terms of the threshold value so should we in this case be able to use the threshold value in estimating the eye's sensitivity or liability to discomfort under a given lighting condition. Threshold values are usually determined by finding how much energy or intensity of a given stimulus, applied for a short interval of time, is required to arouse a just noticeable sensation. This form of procedure, however, is not adapted to the needs of our problem. It is much better to reverse the process and find how long the eye has to be exposed to a stimulus of a given intensity to arouse just noticeable discomfort. Our threshold thus

becomes a time threshold and is measured in units of time instead of units of intensity. In order to determine whether the judgment of the threshold of discomfort can be made with certainty and to perfect the method and to test in general its feasibility, an abstract investigation was undertaken first, running through an entire year, in which a better and more convenient control of conditions could be secured than is possible in the investigation of a concrete lighting situation. That is, we undertook to determine the comparative sensitivity of the eye to discomfort when a single source of light was exposed in different parts of the field of vision. In order to carry out this investigation a lamp house with a circular opening in one side 3 cm. in diameter was attached to the arm of a perimeter in such a way that the opening was always directed towards the observer's eye. In the lamp house could be placed a lamp of whatever candlepower was desired. The arm of the perimeter could be shifted to any meridian in which it was desired to work and the lamp house could be moved at will along this arm. It was thus possible to expose the light for any length of time in any part of the field of vision that was desired. Working in this way we have not only investigated the effect of many types of variation of the position of the light in the field of view, the effect of intensity of light, etc.; but we have studied and standardized the factors that influence the sensitivity and reproducibility of the judgment and have given our observers the training that was needed for the concrete investigation. In making the concrete investigation we have used every variation of the conditions of lighting described in this and the preceding paper. That is, the tendency to produce discomfort, measured in terms of the value of the time threshold, has been determined for all the conditions of lighting we have used in the tests for loss of efficiency. Two cases may be made of the investigation,—a determination of the tendency to cause discomfort when the eye is at rest, and a determination of this tendency when the eye is at work. Both of these cases were included in our investigation. The following determinations were made. (a) The time threshold of discomfort was gotten when the observer was sitting with the accommodation muscles relaxed and with the fixation muscles as nearly relaxed as was practica-

TABLE XXIII.—DISTRIBUTION SERIES.

Showing a comparison of the tendency of the direct, semi-indirect, and indirect installations of lighting used in the distribution series to cause loss of efficiency and to produce discomfort. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Position of observer	Lighting system	Watts	Foot-candles		45°	Per cent. loss of efficiency	Time linen of discomfort in seconds	
			Horizontal	Vertical			(not reading)	(reading)
I.	Indirect	800	5.2	1.36	3.5	8.6	263	100
	Semi-indirect	760	5.8	1.45	4.0	72.0	15	8
	Direct	880	4.2	1.41	2.6	81.0	10	9
II.	Indirect	800	5.1	1.98	4.2	6.3	259	103
	Semi-indirect	760	6.1	2.5	4.7	37.0	26	14
	Direct	880	4.65	2.75	4.4	58.3	20	13
III.	Indirect	800	3.9	2.1	4.0	7.7	255	99
	Semi-indirect	760	5.0	2.6	5.4	22.0	120	35
	Direct	880	4.0	2.9	4.6	31.0	55	24
IV.	Indirect	800	2.9	2.1	3.6	6.6	265	101
	Semi-indirect	760	3.4	3.0	4.4	19.0	240	87
	Direct	880	3.0	3.4	4.5	23.0	235	57

TABLE XXIV.—INTENSITY SERIES.

Showing a comparison of the tendency of the direct, semi-indirect and indirect installations of lighting for the different intensities used in the intensity series to cause loss of efficiency and to produce discomfort. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Lighting system	Watts	Foot-candles			Per cent. loss in efficiency	Time linen of discomfort in seconds (not reading)	Time linen of discomfort in seconds (reading)
		Horizontal	Vertical	45°			
Indirect.....	800	5.2	1.36	3.5	8.6	263.0	100
	480	3.0	0.765	1.97	8.0	265.0	103
	320 (with socket extenders)	1.7	0.49	1.08	9.1	256.0	98
	200 (with socket extenders)	1.48	0.407	0.95	5.7	251.0	104
	320 (without socket extenders)	1.33	0.39	0.87	23.0	50.0	33
	200 (without socket extenders)	1.16	0.37	0.76	40.0	20.0	14
Semi-indirect.....	320	2.2	0.58	1.52	11.4	102.0	35
	200	1.6	0.45	1.15	40.9	62.0	16
	480	3.3	0.94	2.4	50.0	50.0	15
	760	5.8	1.45	4.0	72.0	15.0	8
	800	6.8	1.82	4.5	78.0	14.0	3
	240	1.23	0.54	0.935	57.4	23.5	17
Direct (16 lamps).	365	1.6	0.6	1.33	62.0	14.0	11
	400	1.86	0.8	1.46	65.0	12.0	11
	880	4.2	1.41	2.6	81.0	10.0	9
	200	1.16	0.45	0.85	34.3	56.0	27
	120	0.64	0.32	0.49	45.5	52.0	15
	320	1.97	0.65	1.39	55.5	23.0	13
Direct (8 lamps) ..	480	2.6	1.02	2.00	67.0	20.0	12

ble under the conditions. That is, the observer sat in the positions shown in Fig. 1, p. 452a, and took an easy fixation of an area at the level of the eye on the opposite wall of the room. The fixation distance, for example, for Position I, Fig. 1, p. 452a, was 22 ft. Since blinking was found to be one of the variable factors which influ-

TABLE XXV.—EYE SHADE SERIES.

Showing a comparison of the tendency of the direct, semi-indirect, and indirect installations of lighting used in the distribution series to cause loss of efficiency and to produce discomfort when the eye was protected by an opaque eye shade with a dark lining and by an opaque eye shade with a white lining. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Lining of eye shade	Lighting system	Watts	Foot-candles			Per- cent. loss of effi- ciency	Time limen of discomfort	Time limen of discomfort
			Hori- zontal	Verti- cal	45°		in sec- onds (not read- ing)	in sec- onds (read- ing)
White	Indirect	800	5.2	1.36	3.5	9.1	85	50
	Semi-indirect	760	5.8	1.45	4.0	10.6	81	48
	Direct	880	4.2	1.41	2.6	12.0	75	45
Dark	Indirect	800	5.2	1.36	3.5	33.0	23	19
	Semi-indirect	760	5.8	1.45	4.0	33.4	19	15
	Direct	880	4.2	1.41	2.6	35.0	16	13

TABLE XXVI.—THE ANGLE AT WHICH THE LIGHT FALLS ON THE WORK.

Showing a comparison of the tendency to cause loss of efficiency and to produce discomfort of the angle at which the light falls on the work. The loss of efficiency is the result of three hours of work. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

Kind of reflection from reading page	Foot-candles			Per cent. loss of efficiency	Time limen of discomfort in seconds (reading)
	Horizontal	Vertical	45°		
Diffuse	5.3	1.84	3.9	6.6	95
Specular	5.3	1.84	3.9	14.3	30

ence the tendency to produce discomfort, the amount of blinking was made constant from test to test. This was accomplished by having the observer blink at equal intervals during the test, timing himself by means of the stroke of a metronome. The interval most natural and suitable for this purpose was determined for

each observer separately. In the results given in the following table a three-second interval was used. And (b) the time threshold of discomfort was determined when the observer was reading from print and paper similar to that used in the loss of efficiency tests. In these tests all the conditions were kept as nearly the same as they were in the work on loss of efficiency as was possible. The results of both of these sets of experiments on the tendency to produce discomfort are shown in Tables XXIII–XXVI. The tendency to produce discomfort should be estimated, roughly speaking, probably as inversely proportional to the time it was required for discomfort to be set up. The time required for discomfort to be set up is given in the tables. In order to make convenient a comparison of the tendency of the various conditions of lighting to cause loss of efficiency and to produce discomfort the percentage loss of efficiency caused by the given lighting conditions is given in a parallel column in each table. The percentage loss of efficiency was computed by dividing the loss in the ratio of time seen clear to time seen blurred sustained as a result of work by 3.5, the standard ratio to which all the ratios at the beginning of work were reduced. A rough correspondence of the tendency to produce discomfort and to cause loss of efficiency will be noted in every case. This correspondence by no means amounts to a 1 : 1 correlation, however. In Table XXIII is given the comparison of the tendency to cause loss of efficiency and to produce discomfort for the distribution series; in Table XXIV, for the intensity series; in Table XXV, for the eye shade series; and in Table XXVI, for the series showing the effect of the angle at which the light falls on the work.

In conclusion we wish to state that in this work, and the work reported in the former papers, the purpose has been primarily to procure methods of working and to find out, as broadly as one may, the applicability of these methods to the problems surrounding the hygiene of the eye. While in many places attention has been called to results that seemed to have general significance, the intention has been, in general, to limit all comments and conclusions strictly to the conditions under which the work was done.

A RÉSUMÉ OF EXPERIMENTS ON THE PROBLEM OF LIGHTING IN ITS RELATION TO THE EYE

THE work of which this paper is a brief outline was done under the auspices of the American Medical Association. The object of the work has been to compare the effect of different lighting conditions on the eye and to find the factors in a lighting situation which cause the eye to lose in efficiency and to experience discomfort.

Confronting the problem of the effect of different lighting conditions on the eye, it is obvious that the first step towards systematic work is to obtain some means of estimating effect. The prominent effects of bad lighting systems are loss of efficiency, temporary and progressive, and eye discomfort. Three classes of effect, however, may be investigated: (1) the effect on the general level or scale of efficiency for the fresh eye; (2) loss of efficiency as the result of a period of work; and (3) the tendency to produce discomfort. A description of tests designed especially for the investigation of these

effects has already appeared in print.¹ The test for the second effect, it may be mentioned, is not analytical in nature. Its results express an aggregate loss of function. Supplementary tests have been devised, therefore, by means of which the factors contributive to a given result may be separated out. A description of these tests is also included in the papers referred to above.

The following aspects of lighting sustain an important relation to the eye: the evenness of illumination, the diffuseness of light, the angle at which the light falls on the object viewed, the evenness of surface brightness, intensity, and quality. The first four of these factors, which may be grouped together as distribution factors, will be discussed briefly with reference to types of lighting now in common use.

The ideal condition with regard to the distribution factor is to have the field of vision uniformly illuminated with light well diffused and no extremes of surface brightness. When this condition is attained the illumination of the retina will shade off more or less gradually from center to periphery, which gradation is necessary for accurate and comfortable fixation and accommodation. In the proper illumination of a room by daylight, we have been able thus far to get the best conditions of distribution. Before it reaches our windows or skylights, daylight has been rendered widely diffuse by innumerable reflections; and the windows and skylights themselves acting as sources have a broad area and low intrinsic brilliancy, all of which features contribute towards giving the ideal conditions of distribution stated above. Of the systems of artificial lighting the best distribution effects, speaking in general terms, are given by the indirect systems, and the semi-indirect systems with a small direct component of light. In the indirect systems the

¹ Ferree, C. E. "Tests for the Efficiency of the Eye under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort," *Trans. Ill. Eng. Soc.* 1913, 8, pp. 40-60; "Untersuchungsmethoden für die Leistungsfähigkeit des Auges bei verschiedenen Beleuchtungssystemen, und eine vorläufige Untersuchung über die Ursachen unangenehmer optischer Empfindungen," *Z. f. Sinnesphysiol.*, 1915, 49, pp. 59-78; "The Efficiency of the Eye under Different Systems of Lighting," *Fourth Intern. Congress on School Hygiene*, Buffalo, 1913, 5, pp. 351-364; "Ophthalmology," July, 1914, pp. 1-16; "Mind and Body," 1913, 20, pp. 280-286, 345-353; "The Problem of Lighting in Its Relation to the Efficiency of the Eye," *Science*, July 17, 1914, N. S., 15, pp. 84-91; Ferree, C. E. and Rand, G. "The Efficiency of the Eye under Different Conditions of Lighting: The Effect of Varying Distribution and Intensity," *Trans. Illum. Eng. Soc.*, August, 1915, 10, pp. 407-447; "Further Experiments on the Efficiency of the Eye under Conditions of Lighting," *Trans. Ill. Eng. Soc.*, August, 1915, 15, pp. 448-504. See also J. R. Cravath. "Some Experiments with the Ferree Test for Eye Fatigue," *Trans. Ill. Eng. Soc.*, 1914, 9, pp. 1033-1047; also C. E. Ferree, "Discussion of Mr. Cravath's Paper, Some Experiments," etc., *ibid.*, pp. 1050-1059.

source is concealed from the eye and the light is thrown against the ceiling or some other diffusely reflecting surface in such a way that it suffers one or more reflections before it reaches the eye. In some of the respects most important to the eye, this and the semi-indirect systems with a small direct component of light give the best approximation of the distribution effects characteristic of daylight of any that have yet been devised. The direct lighting systems are designed to send the light directly to the plane of work. There is in general in the use of these systems a tendency to concentrate the light on the working plane or object viewed rather than to diffuse it, and to emphasize brightness extremes rather than to level them down. Too often, too, the eye is not properly shielded from the light source and frequently no attempt at all is made to do this. The semi-indirect systems are intended to represent a compromise between the direct and indirect systems. A part of the light is transmitted directly to the plane of work through the translucent reflector placed beneath the source of light, and a part is reflected to the ceiling. Thus, depending upon the density of the reflector, this type of system may vary between the totally direct and the totally indirect as extremes and share in the relative merits and demerits of each in proportion to its place in the scale. By giving better distribution effects this type of system is supposed also to be a concession to the welfare of the eye, but our tests show that the concession, at least for the reflectors of low and medium densities, is not so great as it is supposed to be. In fact, installed at the intensity of illumination ordinarily used or at an intensity great enough for all kinds of work, little advantage seems to be gained for the eye in this type of lighting with reflectors of low or medium densities; for with these intensities of light and densities of reflector, the brightness of the source has not been sufficiently reduced to give much relief to the suffering eye. Until this is done in home, office, and public lighting, we can not hope to get rid of eye strain with its complex train of physical and mental disturbances.

In the experimental work the following points are covered: the effect of varying the distribution factors on the ability of the eye to maintain its maximal efficiency for a period of work; the effect of varying the intensity of light with various groupings of distribution factors; and certain miscellaneous experiments relating to the hygienic employment of the eye. These latter experiments include the effect of varying the area and conversely the intrinsic brightness of the ceiling spots above the reflectors in an indirect system of lighting; the effect of varying the angle at which the light falls on the work in a given lighting situation; the effect of

using an opaque eye-shade with light and dark linings with each of the lighting installations used in the distribution and intensity series; the effect on the efficiency of the fixation muscles of a period of work under each of these installations; the effect of motion pictures on the eye at different distances from the projection screen; and a determination of the tendency of all the conditions of lighting employed to produce discomfort and to cause loss of efficiency.

The investigations are not abstract in character. All the variations obtained were gotten in actual concrete lighting situations by employing lighting installations in common use. In order that a correlation might be made between lighting conditions and the effect on the eye, the following specification of illumination effects was made in each case. (1) A determination was made of the average illumination of the room under each of the installations of lighting used. The room was laid out in 3-ft. squares and illumination measurements were made at 66 of the intersections of these squares and at the point of work. Readings were taken in a plane 122 cm. above the floor with the receiving test-plate of the illuminometer in the horizontal, the 45 deg., and the 90 deg. positions, measuring respectively the vertical, the horizontal, and the 45 deg. components of illumination. The 122 cm. plane was chosen because that was the height of the test object. In the work on the distribution series the illumination was made as nearly as possible equal at the point of work. (2) A determination was made in candle-power per sq. in. of the brightness of prominent objects in the room, such as the test surface; the reflectors for the semi-indirect installation; the reflectors and filament for the direct installation, etc.; the reading-page; the specular reflection from surfaces; etc. The brightness measurements were made by means of a Sharp-Millar illuminometer with the test-plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal. By this method the reflecting surfaces were used as detached test-plates. The readings were converted into candle-power per sq. in. by the following formula:

$$\text{Brightness} = \frac{\text{Foot-candles}}{\pi \times 144}$$

(3) Photographs were made of the room from three positions under each system of illumination.

The tests for the effect on the eye were made at four representative positions in the room. The observers used were all under 26 years of age. A clinic record was made of the eyes of each observer. The following results were obtained.

1. Of the lighting factors that influence the welfare of the eye,

those we have grouped under the heading of distribution are apparently fundamental. They seem to be the most important we have yet to deal with in our search for the conditions that give us the minimum loss of efficiency and the maximum comfort in seeing. If, for example, the light is well distributed in the field of vision, and diffuse, and there are no extremes of surface brightness, our tests indicate that the eye, so far as the problem of lighting is concerned, is practically independent of intensity. That is, when the proper distribution effects are obtained, intensities high enough to give the maximum discrimination of detail may be employed without causing appreciable damage or discomfort to the eye.

2. For the kind of distribution effects given by the direct and semi-indirect reflectors of low or medium densities, our results show that unquestionably too much light is being used in ordinary work for the comfort and welfare of the eye.

3. The angle at which the light falls on the object viewed is an important factor, but not nearly so important, for example, as evenness of surface brightness in the field of vision. Extremes of surface brightness in the field of vision seem to be the most important cause of the eye's discomfort and loss of efficiency in lighting systems as we have them at the present time. In lighting from exposed sources it is not infrequent to find the brightest surface from 1,000,000 to 2,500,000 times as brilliant as the darkest; and from 300,000 to 600,000 times as brilliant as the reading-page. These extremes of brightness in the field of vision are, our tests show, very damaging to the eye.

4. Of the systems of artificial lighting tested thus far, the best results have been obtained for the indirect system, and the semi-indirect systems with reflectors having a high density. By means of these reflectors the light is well distributed in the field of vision and extremes of surface brilliancy are kept within the limits which the eyes are prepared to stand. Considerable loss of efficiency has been found to result from the use of direct reflectors and semi-indirect reflectors of low or medium density.

5. The loss of efficiency sustained by the eye under an unfavorable lighting situation is found to be muscular, not retinal. The retina has been found to lose little if any more in efficiency under one than under another of the lighting systems employed.

6. Loss of efficiency of the fixation muscles is, according to our tests, a very small part of the eye's aggregate loss in muscular efficiency as the result of work under an unfavorable lighting system. The chief loss seems to be sustained by the accommodation muscles or the muscles which adjust the lens of the eye.

7. Eye-shades are apparently not an adequate substitute for

lamp-shades for the protection of the eye from the sources of light. The best results are obtained by means of an opaque eye-shade with a light lining. The usual opaque eye-shades with dark linings, while they shield the eye from the source of light, do not by any means eliminate harmful brightness differences in the field of vision. They in fact create for the eye a very unnatural brightness relation; *i. e.*, they make the whole upper half of the field of vision dark in sharp contrast with the brightly lighted lower half. The direct effect of this is a strong brightness contrast (physiological) over the lower half of the field of vision which causes glare in surfaces which have no glare and increases the glare in surfaces in which glare is already present. Moreover, the unusual and strongly irregular character of the image formed on the retina probably also sets up warfare in the incentives given to the muscles which adjust the eye. That is, the upper half of the field of vision is dark and presents no detail. The effect of this is probably to exert a tendency to cause the muscular relaxation characteristic of the darkened field of vision. The lower half of the field of vision is light and filled with detail. The incentive here is for the best possible adjustment of the eye for the discrimination of detail in the objects viewed, while the rim of the shade, the sharply marked boundary between the light and dark halves of the field of vision and much nearer to the eye than the objects viewed, serves as a constant and consciously annoying distraction to fixation and accommodation. These complex and somewhat contradictory impulses given to the muscles of the eye might very well and doubtless do cause an excessive and unnatural loss of energy and efficiency in case of the prolonged adjustment of the eye needed for a period of work. Translucent shades when made sufficiently opaque to give the necessary reduction to the image of the source, darken too much the upper half of the field of vision and simulate thereby too much the effect given by the opaque shade with the dark lining to give the best results for efficient and comfortable seeing.

8. The observation of motion pictures for two or more hours causes the eye to lose heavily in efficiency. The loss decreases rather regularly with the increase of distance from the projection screen. It seems little if any greater, however, than the loss caused by an equal period of working under much of the artificial lighting now in actual use. In making these tests care was taken to choose a projection apparatus which gave a picture comparatively steady and free from flicker.

9. In all the conditions tested a rather close correlation is found

to obtain between the tendency of a given lighting condition to cause loss of efficiency and to produce discomfort.

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SOME EXPERIMENTS ON THE EYE WITH INVERTED REFLECTORS OF DIFFERENT DENSITIES.*

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Synopsis: In previous papers read before this society by the present writers, the gradation of surface brightness and its distribution in the field of vision were shown to be important factors in the effect of lighting conditions on the eye. In the work described in the present paper, gradation of surface brightness is made the chief variable. Inverted reflectors of six degrees of density are employed, and a correlation is made between the illuminating effects obtained and the tendency to cause loss of power to sustain clear seeing and to produce ocular discomfort.

INTRODUCTION.

This paper is the fourth in a series in which the effect of different conditions of lighting on the eye is investigated. In the first paper, two tests were described—one designed to be used as a general test for detecting the comparative tendencies of different lighting conditions to cause a loss in the eye's power to sustain clear seeing for a period of work; the other for detecting the tendency to produce ocular discomfort. In the second paper, the application of the first of these tests to various lighting conditions was begun. Two purposes were had in making this application: (1) the studying and perfecting of the test itself for use in lighting work, which it is obvious could not be done effectively under one set or type of lighting conditions;¹ and (2), the investigation of pertinent lighting effects, the results of which could be made both to serve as a guide for further work, and to provide cumulative data from which conclusions may be drawn as the conditions and stage of advancement of the work may warrant. This paper was divided into two sections. In the first the test was applied to the determination of the effect on the eye of three lighting installations, direct, semi-indirect and indirect, so selected as to give wide differences in illuminating effects. In the second section the effect of six variations in intensity for the direct and semi-indirect installations was determined. In both

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of these cases the tests were all made at one position in the room, the point marked as the position of the observer in Fig. 1 of the present paper. Obviously, however, the effect of an unfavorable installation on the eye will vary with the position of the observer in the room. In the third paper, therefore, the tests were repeated for these installations at four positions in the room: the first with six reflectors in the field of view; the second with four; the third with two, and the fourth with none. The following features were also included: the work of the intensity series was completed, *i. e.*, six intensities of light were used with the indirect reflectors; a test was described for determining the effect on the fixation muscles of the eye; and a series of miscellaneous experiments was conducted pertaining to the hygienic employment of the eye. In these experiments the following points were taken up: the effect of varying the area, and conversely the intrinsic brilliancy of the ceiling spots above the reflectors of the indirect system of lighting used; the effect of varying the angle at which the light falls on the work in a given lighting situation; the effect of using an opaque eye-shade with dark and light linings with a number of lighting installations; the effect on the efficiency of the fixation muscles of three hours of work under each of these installations; the effect of motion pictures on the eye for different distances of the observer from the projection screen; and a determination of the tendency of the different conditions of lighting used in these experiments to produce ocular discomfort, and a comparison of the tendency to produce discomfort and to cause loss of efficiency.

Time cannot be taken here even for a brief statement of the results obtained in these experiments. For the purpose of this paper, it will be sufficient to say that gradation of surface brightness and its distribution in the field of vision were shown to be important factors in the effect on the eye. In the work to be described in the present paper, gradation of surface brightness has been made the chief variable. Inverted opal glass reflectors of six degrees of density have been employed and a correlation has been obtained between the illuminating effects produced and their tendency to cause loss of efficiency and to produce ocular discomfort. As the work progresses, an attempt will be made

not only to investigate this factor further in some of its more important relations to lighting practise, but to take up in turn, so far as is practicable, each of the other factors mentioned in the former papers.²

CONDITIONS TESTED

An effort has been made to get a series of reflectors similar in size and shape and differing only in density. It is our ultimate purpose to use these reflectors both in accord with the principles of direct and indirect lighting, and by employing additional translucent and opaque reflectors, differing if need be in size and shape, to vary first one and then the other of the distribution factors mentioned in the former papers. So far, however, we have been able to use only six of the number of reflectors needed to carry out this plan, and these in accord with the principle of indirect lighting. They were all turned towards the ceiling and were installed the same distance from it. So installed, as the photometric measurements will show, the chief variables have been the brightness of the reflectors and the ceiling spots above the reflectors,—more especially, the brightness of the reflectors. The reflectors used will be designated here by the numerals, I, II, III, IV, V and VI; and will be described in greater detail in an appendix to the paper. They were all installed 30 in. (0.76 m.) from the ceiling³ and were held by Plume and Atwood semi-indirect holders attached to cords dropped from the eight outlets shown in Fig. 1.

It has been our wish to conduct this investigation, as has been the case in all our work on the distribution factors, with the quality and intensity of the light made approximately the same. Unfortunately, with the material available, the quality of the light could not be made in all cases uniformly alike. Clear tungsten lamps were used as light sources with each installation, but two of the reflectors, I and II, were not free from color. The density of these reflectors had been secured in part, by giving them a brownish tone. Just how much effect this would have, if any, on the results of the tests we are not prepared at this time to say. The fact should be borne in mind, however, in considering the results obtained. It was decided to make the intensity of light as nearly equal as possible at the test object and to give a

supplementary specification of the lighting effects in the remainder of the room.

At the test object the light was photometered in several directions. It was made approximately equal in the plane of the test object and as nearly as possible equal in the other directions. The specification of the lighting effects in the remainder of the room was accomplished as follows. (1) A determination was made of the average illumination of the room under each set of reflectors. The room was laid out in 3 ft. (0.90 m.) squares and

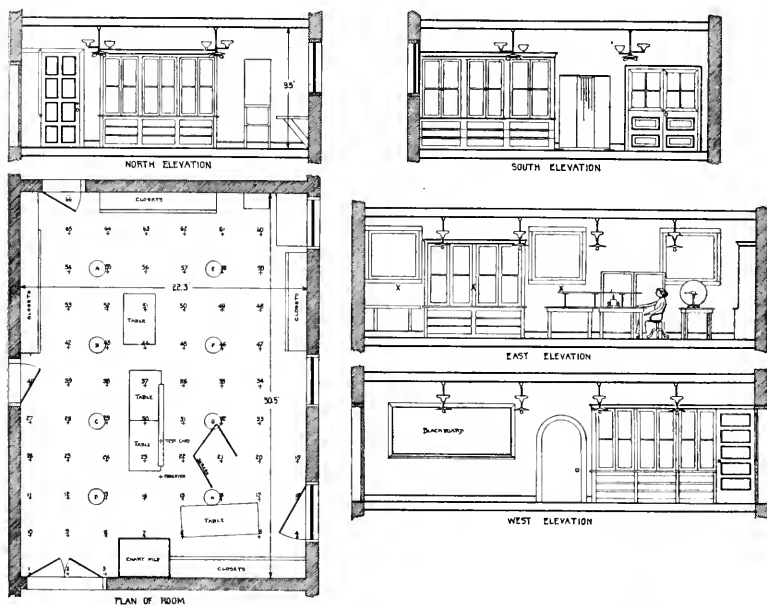


Fig. 1.—Plan of test room.

illumination measurements were made at 66 of the intersections of the sides of these squares. Readings were taken in a plane 122 cm. above the floor with the receiving test-plate of the illuminometer in the horizontal, the 45° and 90° positions, measuring respectively, the vertical, the 45° and horizontal components of illumination. The 122 cm. plane was chosen because that was the height of the test object. (2) A determination was made of the brightness of prominent objects in the room, such as the test card, the reflectors, the reading page, the specular reflection from

surfaces, etc. The brightness measurements were made by means of a Sharp-Millar photometer with the receiving test-plate removed. The instrument was calibrated against a magnesium oxide surface obtained by depositing the oxide from the burning metal on a white card. By this method the reflecting surfaces were used as detached test-plates. The readings were converted into candlepower per square inch by the following formula: $\text{brightness} = \text{foot-candles}/\pi \times 144$. (3) Photographs were made of the room for each set of reflectors employed. They will not all be included in this paper, however, because too little difference in illuminating effects is shown for the different reflectors to warrant so extensive a use of the photographic method of specification.

The tests were conducted in a room 30.5 ft. (9.29 m.) long, 22.3 ft. (6.797 m.) wide, and 9.5 ft. (2.895 m.) high. In Fig. 1, this room is shown drawn to scale: plan of room, north, south, east and west elevations. In the plan of room are shown the 66 stations at which the illumination measurements were made; and the positions of the outlets for the lighting fixtures, A, B, C, D, E, F, G and H. In the drawing, east elevation, the position of the observer at which the tests were taken is represented.⁴ So far in the work with these reflectors the tests have been made at only one point in the room.

Table I gives the illumination measurements for each of the 66 stations represented in Fig. 1. These measurements were made with the receiving test-plate of the illuminometer in the horizontal, the vertical and the 45° planes. Tables II and III have been compiled to supplement Table I for the purpose of making a comparative showing of the evenness of illumination at the 122-cm. level given by the six sets of reflectors. Two cases may be made of this: (1) a comparison may be made of a given component from station to station; or (2) the difference between the components may be compared. To facilitate these comparisons (a) the mean variation from the average of each of the components has been computed; and (b) the difference in the average of the three components has been determined. Results for the first of these points are shown in Table II; and for the second in Table III.

TABLE I.

Showing the illumination measurements in foot-candles for each of the 66 stations represented in Fig. 1 for the six types of reflectors used.

Division A.

Station	Horizontal, reflector type			Vertical, reflector type			45°, reflector type		
	I	II	III	I	II	III	I	II	III
1	1.40	1.35	1.30						
2	1.50	1.28	1.20						
3	1.49	1.52	1.27						
4	1.85	1.46	1.47						
5	2.40	2.20	2.0						
6	2.20	2.40	2.10						
7	2.60	2.50	2.30						
8	2.90	3.10	2.90						
9	2.70	2.60	2.50						
10	1.54	1.41	1.32						
11	2.10	1.88	1.78						
12	3.90	4.30	3.70	0.55	0.53	0.50	2.10	2.0	1.72
13	4.50	4.90	4.50	0.58	0.55	0.49	2.30	2.70	2.40
14	3.20	3.40	3.50	0.50	0.46	0.48	1.65	1.70	1.90
15	3.10	3.10	3.20	0.52	0.40	0.42	1.62	1.70	1.69
16	4.50	4.40	4.30	0.50	0.41	0.50	2.50	2.20	2.10
17	3.80	3.10	3.10	0.54	0.40	0.43	2.20	1.48	1.62
18	2.60	1.86	1.90	0.57	0.46	0.45	1.50	1.10	0.97
19	3.30	2.40	2.50	1.25	0.87	0.93	2.40	1.60	1.90
20	4.10	3.70	3.70	1.17	1.0	0.94	2.70	2.20	2.20
21	5.20	4.60	4.50	1.30	1.30	1.22	3.10	2.90	2.70
22	4.0	3.50	3.80	1.16	1.0	0.94	2.50	2.20	2.30
23	4.0	3.70	3.70	1.10	1.06	1.20	2.60	2.30	2.10
24	4.90	4.90	4.70	1.1	1.20	0.97	3.0	2.70	2.80
25	3.90	4.10	4.20	1.03	0.91	0.95	2.40	2.30	3.30
26	2.50	2.10	1.78						
27	2.80	2.80	2.40						
28	4.80	5.85	4.70	1.15	1.05	1.20	3.40	3.0	3.20
29	5.80	6.0	6.20	1.34	1.35	1.25	3.80	4.0	4.0
30	4.50	3.80	4.50	1.42	1.11	1.37	3.40	2.70	3.10
31	4.50	3.90	4.60	1.42	1.15	1.14	3.30	2.50	3.0
32	5.60	5.30	5.60	1.42	1.33	1.32	4.0	3.70	3.40
33	5.0	3.60	4.25	1.52	1.10	1.15	3.30	2.60	2.80
34	4.70	3.80	3.80	1.86	1.54	1.42	3.70	2.90	2.80
35	5.20	4.90	5.0	2.10	1.64	1.60	4.40	3.50	3.80
36	4.50	4.10	4.50	1.80	1.61	1.48	3.60	2.80	3.30
37	4.60	4.0	4.60	1.99	1.54	1.66	3.70	3.0	3.50
38	4.90	5.40	5.40	2.0	1.90	1.80	4.0	3.80	4.20
39	4.10	4.10	4.0	1.72	1.68	1.50	3.20	3.10	3.20
40	2.60	2.40	2.0						
41	2.0	1.67	1.62						

TABLE I.—(Continued.)

Station	Horizontal, reflector type			Vertical, reflector type			45°, reflector type		
	I	II	III	I	II	III	I	II	III
42	3.90	4.40	4.40	1.80	1.60	1.64	3.40	3.20	3.40
43	5.40	5.40	5.60	2.20	1.86	1.84	4.70	4.0	4.40
44	4.40	4.10	3.70	2.10	1.76	1.50	4.0	3.40	3.20
45	4.10	4.30	4.20	2.10	1.71	1.68	3.80	3.40	3.30
46	5.20	5.60	5.70	2.10	1.60	1.68	4.60	4.10	4.40
47	4.50	4.20	4.50	1.76	1.58	1.52	3.60	3.30	3.30
48	3.90	3.70	3.80	2.0	1.94	1.76	3.60	3.30	3.30
49	4.90	4.80	5.10	2.30	2.10	2.0	3.90	4.20	3.80
50	4.10	3.60	4.0	2.30	2.0	2.10	3.80	3.50	3.40
51	3.90	3.70	3.90	2.30	1.90	1.98	3.70	3.30	3.50
52	4.40	4.50	4.60	2.30	1.95	2.0	4.10	3.70	3.90
53	3.60	3.70	3.80	2.0	1.58	1.80	3.30	3.20	3.20
54	3.10	3.50	3.40	1.70	1.48	1.46	3.20	2.90	3.10
55	4.10	4.30	4.10	2.30	1.70	1.80	4.20	3.80	3.70
56	3.60	3.0	3.30	2.10	1.80	1.86	3.50	3.10	3.60
57	3.60	3.0	3.80	2.30	1.82	2.0	3.50	3.0	3.70
58	4.40	4.40	5.40	2.10	2.10	2.10	4.20	4.10	4.40
59	3.30	3.60	3.60	1.63	1.85	1.66	3.0	3.20	3.20
60	3.0	2.60	2.90	2.0	1.90	1.66	3.50	3.10	3.20
61	3.10	2.90	3.20	2.50	2.0	2.0	3.90	3.60	3.90
62	2.60	2.60	2.50	2.20	2.10	1.92	3.50	3.40	3.20
63	2.50	2.50	2.10	2.20	2.15	2.60	3.40	3.40	3.10
64	3.10	2.30	3.0	2.40	2.0	2.10	4.0	3.30	3.60
65	2.40	2.40	2.30	1.98	1.65	1.59	3.10	2.70	2.80
66	1.23	1.25	1.20						
Average	3.61	3.45	3.49	1.65	1.44	1.43	3.31	2.98	3.05

Division B.

Station	Horizontal, reflector type			Vertical, reflector type			45° reflector type		
	IV	V	VI	IV	V	VI	IV	V	VI
1	1.50	1.45	1.37						
2	1.32	1.36	1.30						
3	1.42	1.40	1.35						
4	1.50	1.53	1.58						
5	2.30	2.50	2.40						
6	2.70	2.30	2.40						
7	2.60	2.60	2.50						
8	3.40	3.60	3.30						
9	2.80	2.80	2.80						
10	1.55	1.48	1.56						
11	2.00	1.94	2.00						
12	4.20	4.30	4.10	0.65	0.51	0.53	2.60	2.40	2.10
13	4.70	5.40	4.90	0.59	0.58	0.60	2.90	3.10	2.90
14	3.60	3.40	3.60	0.56	0.49	0.50	1.88	1.88	1.92

TABLE I.—(Continued.)

Station	Horizontal, reflector type			Vertical, reflector type			45°, reflector type		
	IV	V	VI	IV	V	VI	IV	V	VI
15	3.10	3.40	3.30	0.58	0.49	0.43	1.72	1.80	1.80
16	4.40	4.70	4.80	0.55	0.40	0.56	2.30	2.70	2.60
17	3.10	3.60	3.70	0.44	0.43	0.50	1.64	1.85	2.0
18	1.88	1.96	2.0	0.49	0.51	0.57	1.14	1.15	1.15
19	2.75	2.60	2.80	1.25	1.10	1.13	2.10	1.88	1.84
20	4.20	3.80	4.30	1.20	1.20	1.18	2.70	2.30	2.60
21	4.60	5.0	5.0	1.22	1.48	1.36	2.80	2.50	3.20
22	3.70	3.80	4.10	1.18	1.05	1.04	2.50	2.40	2.50
23	3.80	4.40	4.20	1.15	1.26	1.06	2.30	2.70	2.50
24	5.20	5.90	5.70	1.47	1.52	1.27	3.20	3.30	3.0
25	4.90	4.50	4.30	1.25	1.31	1.07	2.90	2.80	2.40
26	2.40	2.50	2.20						
27	2.70	2.80	2.75						
28	5.10	4.90	5.20	1.45	1.24	1.14	3.80	3.40	3.60
29	5.60	6.10	6.40	1.54	1.34	1.35	4.30	4.40	4.60
30	4.30	4.30	4.50	1.37	1.27	1.36	3.20	3.0	3.50
31	4.20	4.0	4.40	1.30	1.26	1.30	3.0	2.90	3.30
32	5.60	5.80	6.20	1.38	1.40	1.53	3.70	4.25	4.5
33	4.10	4.50	4.80	1.42	1.28	1.38	3.10	3.40	3.80
34	4.0	4.0	4.20	1.80	2.0	1.88	3.0	3.30	3.50
35	5.40	5.60	5.80	2.10	2.20	2.40	4.0	4.0	4.40
36	4.40	4.30	4.50	1.70	2.0	1.98	3.40	3.50	3.60
37	4.30	4.40	4.30	1.88	1.96	1.92	3.40	3.30	3.50
38	5.20	5.0	5.50	2.30	2.30	2.20	4.60	4.10	4.40
39	4.30	4.20	4.50	2.20	1.68	1.90	3.80	3.30	3.70
40	2.60	2.40	2.60						
41	1.80	1.81	1.92						
42	4.50	4.20	4.40	1.82	1.90	1.85	3.50	3.60	3.80
43	5.40	5.50	5.80	2.10	2.10	2.10	4.50	4.30	4.80
44	3.80	3.70	4.50	1.90	2.10	2.0	3.30	2.70	3.90
45	4.20	4.40	4.60	1.90	1.90	1.98	3.60	3.90	3.90
46	5.40	5.80	6.20	1.90	1.85	1.88	4.30	4.70	4.60
47	3.90	4.0	4.50	1.80	1.78	1.72	3.60	3.30	3.80
48	3.60	3.70	4.50	1.91	1.94	2.30	3.20	3.30	4.0
49	5.0	4.90	5.30	2.20	2.60	2.60	4.50	4.60	4.80
50	3.90	4.0	4.20	2.40	2.20	2.80	3.70	3.70	4.20
51	3.90	3.80	4.20	2.40	2.20	2.60	3.70	3.60	4.10
52	4.65	4.70	5.0	2.50	2.50	2.50	4.10	4.20	4.20
53	4.0	3.50	4.0	2.10	2.10	2.10	3.50	3.20	3.60
54	3.70	3.50	3.80	1.74	1.70	1.82	3.20	3.30	3.60
55	4.20	4.70	5.0	2.40	2.0	2.20	4.0	4.30	4.90
56	3.20	3.30	3.60	2.20	2.20	2.10	3.50	3.60	3.90
57	3.40	3.50	3.60	2.20	2.30	2.20	3.60	3.80	3.70
58	4.60	5.10	5.20	2.20	2.30	2.40	4.20	4.90	4.60

TABLE I.—(Continued.)

Station	Horizontal, reflector type			Vertical, reflector type			45°, reflector type		
	IV	V	VI	IV	V	VI	IV	V	VI
59	3.90	3.90	4.30	1.78	1.81	2.40	3.20	3.50	4.0
60	2.50	2.50	3.0	2.0	2.20	2.40	3.30	3.70	3.80
61	3.20	3.20	3.80	2.30	2.60	2.40	4.40	4.20	4.6
62	2.30	2.60	2.50	2.10	2.30	2.40	3.20	3.0	3.40
63	2.50	2.40	2.60	2.60	2.80	2.10	3.60	3.80	3.40
64	3.10	2.90	3.0	2.30	2.40	2.40	4.0	4.0	4.0
65	2.30	2.40	2.40	2.0	2.0	2.10	3.10	3.00	3.10
66	1.14	1.16	1.42						
Average	3.80	3.70	4.20	1.675	1.68	1.71	3.30	3.31	3.49

TABLE II.

Compiled from Table I to show a comparison of the evenness of the illumination at the 122-cm. level given by the six types of reflector used.

Type of reflector	Mean variation of components			Percentage of mean variation of components,*		
	Vertical	Horizontal	45°	Vertical	Horizontal	45°
I	0.976	0.516	0.582	27.0	31.3	17.6
II	0.999	0.487	0.576	29.0	33.8	19.3
III	1.066	0.430	0.562	30.5	30.1	18.4
IV	1.21	0.498	0.601	31.8	29.7	18.2
V	1.10	0.539	0.628	29.8	32.1	19.0
VI	1.47	0.574	0.677	35.0	31.2	19.4

TABLE III.

Compiled from Table I to show the difference in the average values of the three components of illumination for the six types of reflector used.

Type of reflector	Difference between components			Percentage of difference between components		
	Vertical and horizontal	Vertical and 45°	45° and horizontal	Vertical and horizontal	Vertical and 45°	45° and horizontal
I	1.96	0.30	1.66	54.3	8.3	50.2
II	2.01	0.47	1.54	58.3	13.6	51.7
III	2.06	0.44	1.62	59.0	12.6	53.1
IV	2.125	0.50	1.625	55.9	13.2	49.2
V	2.02	0.39	1.63	54.6	10.5	49.2
VI	2.49	0.71	1.78	59.3	16.9	51.0

Figs. 2-5 are taken from the series of photographs showing the illumination effects produced by the six types of reflector used.⁵ As was stated earlier in the paper, not so much use has been made of the photographic method of specification in this as in the former papers. In the former papers three photographs were given for each set of reflectors. One of these was taken from the south end of the room at a point 4 ft. (1.22 m.) from the

west wall. This photograph was taken so as to comprehend as much of the room as was possible in one view. It included the greater part of the ceiling, floor, and north wall, six of the fixtures and about one-half of the east wall. Another was taken to show the illumination effects in the west half of the room. This photograph represents the distribution of light and shade on the greater part of the west wall and adjacent ceiling and includes two of the fixtures. A third was taken primarily for showing the brightness measurements of all surfaces having a very high or very low brilliancy in the field of view of the observer. To have carried out this program in full in the present work would have required the insertion here of eighteen photographs. The amount of difference in the distribution of light and shade for the different reflectors was much too small to warrant this. It has in fact been deemed sufficient to include in this paper photographs for only the second and third of these positions and for only two of the sets of reflectors used,—the most opaque and the least opaque. The photographs for the second position are shown in Figs. 2 and 3; for the third, in 4 and 5. In representing the brightness measurements in Figs. 4 and 5, the spot measured is marked by a letter and the numerical value of the brightness measurement in candle-power per square inch is printed near by. The spots are lettered for convenience of reference in the tables of brightness measurements. The photographs were taken from a point directly behind the position of the observer as near to the south wall of the room as was possible; and although not all of the observer's field of view is covered by the brightness measurements made, owing to the narrow field of the camera as compared with the binocular field, still the order of magnitude of brightness differences present in the field of view is well represented by these measurements.

In Tables IV and V are given the brightness measurements of the room for the six sets of reflectors. These tables also include the letters identifying the measurements with the spots measured as shown in Figs. 4 and 5. The distribution of light and shade in the room was so similar for the different sets of reflectors that the spots measured have approximately the same location for each set of reflectors. Two sets of measurements were made of the brightness of the reflectors,—one with the opening of the

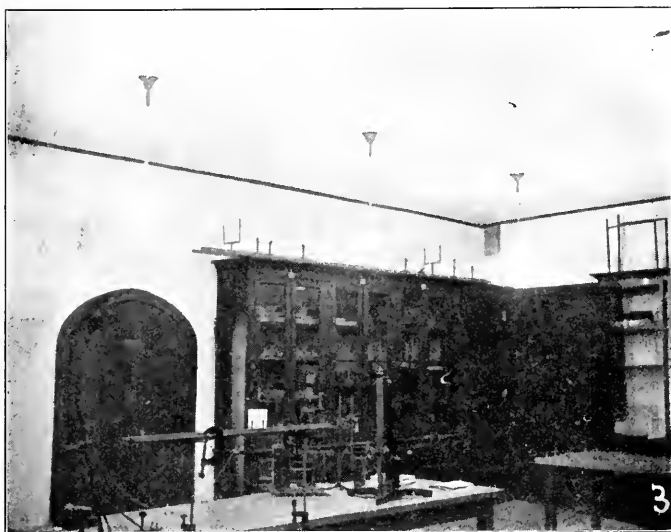


Fig. 2.—Showing the illumination of the west wall of the room, Reflector I.

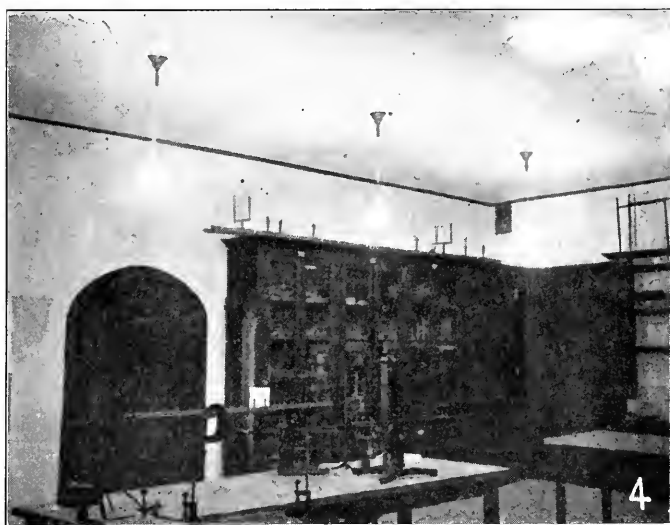


Fig. 3.—Showing the illumination of the west wall of the room, Reflector VI.

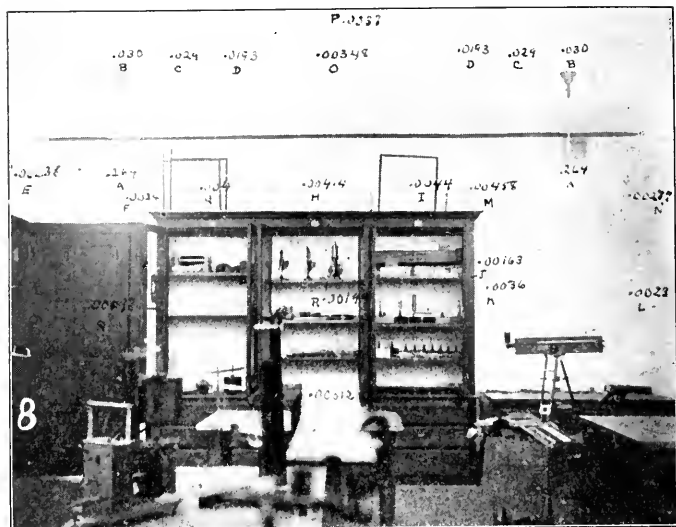


Fig. 4.—Showing the illumination effects in the north end of the room, Reflector I; and the brightness measurements of all surfaces having a very high or a very low brilliancy. This photograph was taken from a point directly behind the observer as near to the south wall of the room as was possible, and comprehends as much of the observer's field of view as could be included in the field of the camera.

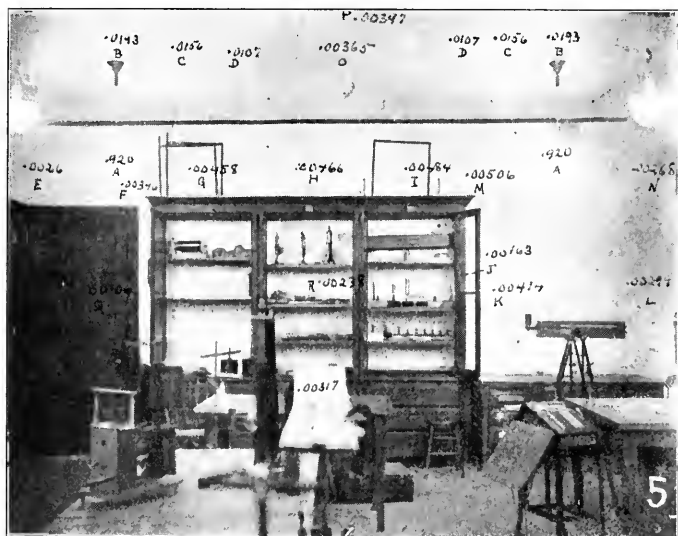


Fig. 5.—Showing the illumination effects in the north end of the room, Reflector VI; and the brightness measurements of all surfaces having a very high or a very low brilliancy. This photograph was taken from a point directly behind the observer as near to the south wall of the room as was possible, and comprehends as much of the observer's field of view as could be included in the field of the camera.

illuminometer close to the reflector and the other with the opening as nearly as possible in the position of the observer when making the test. In the former case the receiving arm was turned normal to the surface measured and the instrument was supported in such a position that the opening was about 4 in. (10.16 cm.) from this surface. The surfaces of some of the reflectors presented so much unevenness of brightness that overlapping measurements were made and an average taken. These average values are given in Table IV. In Table V is given the brightness of the reflectors as measured from the position of the observer. These measurements were taken of the reflectors at outlets A, B and C (Fig. 1) for each of the six installations. A comparison of these measurements will show that reflector B has in each case a higher value than reflector A, and C a higher value than B. Whether or not this can be wholly accounted for because the reflectors were not perfect diffusers we are not prepared to say. That is, the angle subtended by reflector A at the point of observation was less than that subtended by B, and by B less than that subtended by C; so that at the distance at which these reflectors was viewed approximately all of A occupied the field of the illuminometer in making the brightness match, while only the brighter central portions of B and C were comprehended in this field, still less of the duller periphery being included for C than for B.

In Tables VI and VII, are shown some prominent ratios of surface brightness for the six sets of reflectors. In compiling these ratios it has been considered important to make a comparative showing for the different types of reflectors (*a*) of the extremes of surface brightness and (*b*) of the relation of the brilliancy of objects in the surrounding field to the surface brightness at the point of work. Extremes of surface brightness are shown by giving the ratios between surfaces of the first, second, third, etc., order of brilliancy and the lowest order of brilliancy; and the comparison of the brilliancy of objects in the surrounding field to the brightness at the point of work by giving the ratios of the surfaces of the first, second, and third order of brilliancy to the brightness of the test card and the reading page in the working position.

TABLE IV.

Showing the brightness measurements in candlepower per square inch for the surfaces A, B, C, D, etc. (Figs. 4 and 5), the test card and reading page. These measurements were taken with the illuminometer close to the surface measured and with its receiving arm normal to this surface.

Surface measured	Reflector type I.	Reflector type II	Reflector type III	Reflector type IV	Reflector type V	Reflector type VI
A.....	0.264	0.361	0.392	0.614	0.848	0.920
B.....	0.030	0.01985	0.024	0.0101	0.0137	0.0193
C.....	0.029	0.021	0.021	0.0123	0.0166	0.0156
D.....	0.0193	0.0106	0.0075	0.0070	0.00767	0.0107
E.....	0.00238	0.00246	0.00229	0.00282	0.00255	0.0026
F.....	0.0034	0.00394	0.0034	0.00396	0.00396	0.00396
G.....	0.0040	0.00392	0.0042	0.00497	0.00418	0.00458
H.....	0.00414	0.00396	0.0044	0.00506	0.0043	0.00466
I.....	0.0044	0.00402	0.00453	0.00528	0.0042	0.00484
J.....	0.00163	0.0011	0.00128	0.00141	0.00123	0.00163
K.....	0.0036	0.00387	0.00414	0.0044	0.00425	0.00414
L.....	0.0023	0.00224	0.00282	0.00299	0.00273	0.00299
M.....	0.00458	0.00405	0.00484	0.0052	0.00427	0.00506
N.....	0.00277	0.00216	0.00216	0.00334	0.00268	0.00268
O.....	0.00348	0.00299	0.00462	0.00361	0.00361	0.00365
P.....	0.0037	0.00312	0.00506	0.00409	0.0037	0.00397
Q.....	0.00097	0.00083	0.00106	0.00099	0.000924	0.00106
R.....	0.00199	0.0029	0.00207	0.00220	0.00246	0.00238
Test card.	0.00312	0.00308	0.00308	0.00317	0.00312	0.00317
Reading page hori- zontal..	0.00528	0.00497	0.00506	0.0052	0.00484	0.00484
Reading page 45° po- sition..	0.00352	0.00348	0.00352	0.00348	0.00334	0.00339

TABLE V.

Showing the brightness measurements in candlepower per square inch of the reflectors used when the measurements are made from the position occupied by the observer during the test. In these measurements the receiving arm of the illuminometer was placed as nearly as possible in the position of the observer's eye during the test, and was pointed at the reflector. The position of the reflector in each case is shown by the letters A, B and C in Fig. 1.

Position of reflector	Reflector type I	Reflector type II	Reflector type III	Reflector type IV	Reflector type V	Reflector type VI
A.....	0.119	0.156	0.180	0.2325	0.327	0.382
B.....	0.1755	0.1913	0.2025	0.2535	0.338	0.405
C.....	0.2025	0.338	0.397	0.544	0.722	0.830

Supplementary to Tables IV, VI and VII we have computed for the six types of reflector the mean variation of the several brightness values from their average values. While important from the standpoint of showing the variations from the mean for the different types of reflector, such a comparison is, however, probably not so important from the standpoint of the eye as are the comparisons given in Tables IV to VII. That is, from the standpoint of the effect on the eye it is probably more important to give a representation of the brightness of individual surfaces, more especially of surfaces showing extremes of brightness, than it is to give the mean variation from the average brightness of all the surfaces. In order to make possible the comparison with and without the reflector and the spot above the reflector, the table is made to show separately the mean variation of the following measurements: (a) for all: (b) for all but the reflector; and (c) for all but the reflector and the spot above the reflector. Results are given in Table VIII.

As was stated earlier in the paper the effect of a harmful installation on the ability of the eye to maintain its efficiency for a period of work varies with the position of the observer in the room. In the former work the tests were made at four positions, one in which six fixtures were in the field of view; one in which four were in the field of view; one in which two were in the field of view; and one in which none was in the field of view. This variation of the position in which the observation is made accomplishes two purposes: (1) it gives us a more representative idea of the difference of the effect on the eye of the six types of lighting used; and (2) it shows the effect of varying the number of surfaces in the field of view showing brightness differences, particularly the number of primary sources. So far we have been able to conduct the tests for the reflectors used in this work at only one of these positions, namely, the one with six reflectors in the field of view.⁶ Later we expect to repeat the tests for at least a part of these reflectors at the other three positions.

The results for the effect on the eye are given in Table IX.⁷ The values given in this table are averaged in each case from the results of 6 three-hour tests and are typical of the results obtained for all of our observers. In order to show the repro-

TABLE VI.*
 Ratios showing the extremes of surface brightness for the six types of reflectors used.

Ratio	Division A.		Reflector type II		Reflector type III	
	Reflector type I		Reflector type II		Reflector type III	
Lightest to darkest.....	0.264	/0.00097 = 272.0	0.361	/0.00083 = 435.0	0.392	/0.00106 = 370.0
2nd lightest to darkest.....	0.030	/0.00097 = 31.0	0.021	/0.00083 = 25.3	0.024	/0.00106 = 22.6
3rd lightest to darkest.....	0.029	/0.00097 = 29.9	0.01985	/0.00083 = 23.9	0.021	/0.00106 = 19.8
4th lightest to darkest.....	0.0193	/0.00097 = 20.0	0.0106	/0.00083 = 12.8	0.0075	/0.00106 = 7.08
5th lightest to darkest.....	0.00458	/0.00097 = 4.72	0.00405	/0.00083 = 4.88	0.00506	/0.00106 = 4.77
6th lightest to darkest.....	0.0044	/0.00097 = 4.54	0.00402	/0.00083 = 4.84	0.00484	/0.00106 = 4.57
7th lightest to darkest.....	0.00414	/0.00097 = 4.27	0.00396	/0.00083 = 4.77	0.00462	/0.00106 = 4.36
8th lightest to darkest.....	0.0040	/0.00097 = 4.12	0.00394	/0.00083 = 4.75	0.00453	/0.00106 = 4.27
9th lightest to darkest.....	0.0037	/0.00097 = 3.81	0.00392	/0.00083 = 4.72	0.0044	/0.00106 = 4.15
10th lightest to darkest.....	0.0036	/0.00097 = 3.71	0.00387	/0.00083 = 4.66	0.0042	/0.00106 = 3.96
11th lightest to darkest.....	0.00348	/0.00097 = 3.59	0.00312	/0.00083 = 3.76	0.00414	/0.00106 = 3.91
12th lightest to darkest.....	0.0034	/0.00097 = 3.51	0.00299	/0.00083 = 3.60	0.0034	/0.00106 = 3.21
13th lightest to darkest.....	0.00277	/0.00097 = 2.86	0.0029	/0.00083 = 3.49	0.00282	/0.00106 = 2.66
14th lightest to darkest.....	0.00238	/0.00097 = 2.45	0.00246	/0.00083 = 2.96	0.00229	/0.00106 = 2.16
15th lightest to darkest.....	0.0023	/0.00097 = 2.37	0.00224	/0.00083 = 2.70	0.00216	/0.00106 = 2.04
16th lightest to darkest.....	0.00199	/0.00097 = 2.05	0.00216	/0.00083 = 2.60	0.00207	/0.00106 = 1.95
17th lightest to darkest.....	0.00163	/0.00097 = 1.68	0.0011	/0.00083 = 1.33	0.00128	/0.00106 = 1.21

TABLE VI.
Division B.

Ratio	Reflector type IV		Reflector type V		Reflector type VI	
Lightest to darkest	0.614	/0.00099 = 620.0	0.848	/0.000924 = 918.0	0.92	/0.00106 = 868.0
2nd lightest to darkest	0.0123	/0.00099 = 12.4	0.0166	/0.000924 = 18.0	0.0193	/0.00106 = 18.2
3rd lightest to darkest	0.0101	/0.00099 = 10.2	0.0137	/0.000924 = 14.8	0.0156	/0.00106 = 14.7
4th lightest to darkest ..	0.007	/0.00099 = 7.70	0.00767	/0.000924 = 8.30	0.0107	/0.00106 = 10.1
5th lightest to darkest	0.00528	/0.00099 = 5.33	0.0043	/0.000924 = 4.65	0.00506	/0.00106 = 4.77
6th lightest to darkest	0.0052	/0.00099 = 5.25	0.00427	/0.000924 = 4.62	0.00484	/0.00106 = 4.57
7th lightest to darkest	0.00506	/0.00099 = 5.11	0.00425	/0.000924 = 4.60	0.00466	/0.00106 = 4.40
8th lightest to darkest	0.00497	/0.00099 = 5.02	0.0042	/0.000924 = 4.55	0.00458	/0.00106 = 4.32
9th lightest to darkest	0.0044	/0.00099 = 4.44	0.00418	/0.000924 = 4.52	0.00414	/0.00106 = 3.91
10th lightest to darkest	0.00409	/0.00099 = 4.13	0.00396	/0.000924 = 4.29	0.00397	/0.00106 = 3.74
11th lightest to darkest	0.00396	/0.00099 = 4.0	0.0037	/0.000924 = 4.0	0.00396	/0.00106 = 3.73
12th lightest to darkest	0.00361	/0.00099 = 3.65	0.00361	/0.000924 = 3.91	0.00365	/0.00106 = 3.44
13th lightest to darkest	0.00334	/0.00099 = 3.37	0.00273	/0.000924 = 2.95	0.00299	/0.00106 = 2.82
14th lightest to darkest	0.00299	/0.00099 = 3.02	0.00268	/0.000924 = 2.90	0.00268	/0.00106 = 2.53
15th lightest to darkest	0.00282	/0.00099 = 2.85	0.00255	/0.000924 = 2.76	0.0026	/0.00106 = 2.45
16th lightest to darkest	0.0022	/0.00099 = 2.22	0.00246	/0.000924 = 2.66	0.00238	/0.00106 = 2.24
17th lightest to darkest	0.00141	/0.00099 = 1.42	0.00123	/0.000924 = 1.33	0.00163	/0.00106 = 1.54

* It will be noted in Tables IV and VI that while the reflectors grade in brightness from I to VI in an unbroken series, the ratio lightest to darkest for Reflector III is less than for Reflector II, and for Reflector VI than for Reflector V. This in all probability is because of a difference in distribution effects given by these reflectors due to a difference in power to diffuse the light. That is, while the brightest spots (the reflectors) grade in an unbroken series, the darkest spots do not.

TABLE VII.
 Ratios showing the relation of the brilliancy of objects in the surrounding field to the surface brightness
 at the point of work for the six types of reflector used.

Ratio	Division A.		
	Reflector type I	Reflector type II	Reflector type III
Lightest to test card	0.264 / 0.00312 = 84.7	0.361 / 0.00308 = 117.2	0.392 / 0.00317 = 123.7
Lightest to reading page	0.264 / 0.00352 = 75.0	0.361 / 0.00348 = 103.8	0.392 / 0.00348 = 112.6
2nd lightest to test card	0.030 / 0.00312 = 9.61	0.021 / 0.00308 = 6.8	0.024 / 0.00317 = 7.57
2nd lightest to reading page	0.030 / 0.00352 = 8.5	0.021 / 0.00348 = 6.3	0.024 / 0.00348 = 6.9
3rd lightest to test card	0.029 / 0.00312 = 9.29	0.01985 / 0.00308 = 6.46	0.021 / 0.00317 = 6.62
3rd lightest so reading page	0.029 / 0.00352 = 8.2	0.01985 / 0.00348 = 5.70	0.021 / 0.00348 = 6.03

Ratio	Division B.		
	Reflector type IV	Reflector type V	Reflector type VI
Lightest to test card	0.614 / 0.00317 = 193.7	0.848 / 0.00312 = 272.0	0.92 / 0.00317 = 290.2
Lightest to reading page	0.614 / 0.00348 = 176.4	0.848 / 0.00334 = 248.0	0.92 / 0.00339 = 271.0
2nd lightest to test card	0.0123 / 0.00317 = 3.88	0.0166 / 0.00312 = 5.32	0.0193 / 0.00317 = 6.09
2nd lightest to reading page	0.0123 / 0.00348 = 3.53	0.0166 / 0.00334 = 4.97	0.0193 / 0.00339 = 5.7
3rd lightest to test card	0.0101 / 0.00317 = 3.19	0.00137 / 0.00312 = 4.39	0.0156 / 0.00317 = 4.92
3rd lightest to reading page	0.0101 / 0.00348 = 2.90	0.00137 / 0.00334 = 4.1	0.0156 / 0.00339 = 4.6

ducibility of the results obtained and that the variations produced by the changes in lighting effects are much greater than the variations in the test itself, subject to all the variable factors which may influence it, the mean variation from the average result has been computed in each case. The value of this in per cent. is given in column 15.⁸

TABLE VIII.

Compiled from Table IV to show the mean variations in surface brightness for the six types of reflector used.

Measurements considered	Mean variation for the three reflectors			Percentage of mean variation for the three reflectors		
	Reflector type			Reflector type		
	I	II	III	I	II	III
All.....	0.02885	0.0373	0.0405	134.8	148.0	148.4
All but the reflector.....	0.00667	0.00412	0.00411	93.2	75.3	70.3
All but the reflector and the spots above the re- flector.....	0.000917	0.000884	0.0012	29.5	29.7	35.8

Measurements considered	Mean variation for the three reflectors			Percentage of mean variation for the three reflectors		
	Reflector type			Reflector type		
	IV	V	VI	IV	V	VI
All.....	0.06494	0.08852	0.09597	168.0	170.8	170.5
All but the reflector.....	0.0020	0.00274	0.00342	42.4	56.0	62.0
All but the reflector and the spots above the re- flector.....	0.00111	0.000964	0.00104	30.9	30.0	30.2

In Chart 1 a graphic representation is made of the results of this table. In constructing this chart, the total length of the test period is plotted along the abscissa, and the ratio of the time the test object is seen clear to the time it is seen blurred in the three-minute records before and after work is plotted along the ordinate. Each one of the large squares along the abscissa represents one hour of the test period, and along the ordinate an integer of the ratio.

So far in all our work we have shown for the sake of completeness of representation the gradation of surface brightness in three ways.—(1) Brightness measurements of prominent surfaces have been made. (2) Ratios have been given between surfaces of the first, second, third, etc., order of brilliancy and surfaces of the lowest order of brilliancy; and between sur-

TABLE IX.

Showing the tendency of the six types of reflector to cause loss of visual efficiency, or power to sustain clear seeing.

Reflector type	Watts	Intensity foot-candles			Time	Maximal distance at which test object can be seen clear	Working distance	Total time clear	Total time blurred	Total time clear ÷ total time blurred	Ratios reduced to common standard	Loss of efficiency expressed in per-centage drop in ratio	Mean variation (per cent.) ¹⁹
		Horizontal	Vertical	45°									
I	800	111.0	4.1	1.14	2.7	9 A.M. 12 M.	80.2 80.0	62.2 62.2	138.5 133.0	41.5 47.0	3.34 2.83	— 15	— 0.86
II	800	110.0	3.7	1.13	2.6	9 A.M. 12 M.	80.0 79.5	64.0 64.0	139.0 115.0	41.0 65.0	3.39 1.77	— 48	— 0.77
III	800	107.5	4.2	1.16	2.6	9 A.M. 12 M.	80.0 79.5	64.0 64.0	145.0 118.0	35.0 62.0	4.14 1.9	— 54	— 0.70
IV	800	105.5	3.8	1.15	2.5	9 A.M. 12 M.	79.5 79.0	63.6 63.6	145.0 112.0	35.0 68.0	4.14 1.65	— 60	— 2.0
V	800	105.5	3.7	1.15	2.6	9 A.M. 12 M.	79.5 78.5	63.6 63.6	140.1 91.0	39.9 89.0	3.51 1.02	— 71	— 0.86
VI	800	107.5	4.2	1.16	2.7	9 A.M. 12 M.	79.5 78.5	63.6 63.6	141.0 89.0	39.0 91.0	3.62 0.978	— 73	— 1.0

TABLE X

Showing a comparison of the tendency of the six types of reflector used to cause loss of efficiency and to produce ocular discomfort. The tendency to produce discomfort is estimated by the time required for just noticeable discomfort to be set up.

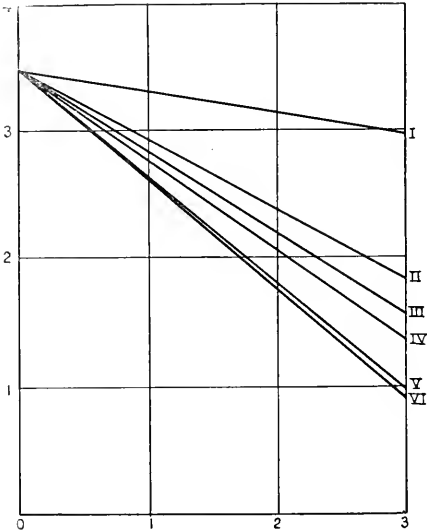
Reflectors	Volts	Foot-candles			Per cent. loss of efficiency	Mean variation (Per cent.)	Time of discomfort in seconds (not reading)	Mean variation (Per cent.)	Change produced by changing type of reflector (Per cent.)	Time of discomfort in seconds (reading)	Mean variation (Per cent.)	Change produced by changing type of reflector (Per cent.)
		Horizontal	Vertical	45°								
Type I ..	111	4.1	1.14	2.7	15	0.86	80	1.1		25	1.6	
Type II ..	110	3.7	1.13	2.6	48	0.77	45	1.5	43.8	17	1.5	32.0
Type III ..	107.5	4.2	1.16	2.6	54	0.70	34	1.8	24.4	14	2.1	17.7
Type IV ..	105.5	3.8	1.15	2.5	60	2.0	21	2.4	38.2	10	2.0	28.6
Type V ..	105.5	3.7	1.15	2.6	71	0.86	17	2.2	19.0	8	2.3	20.0
Type VI ..	107.5	4.2	1.16	2.7	73	1.0	15	2.7	11.8	6.5	3.0	18.8

faces of the first, second and third order of brilliancy and the brightness at the point of work. And (3) the mean variation from the average and the percentage of mean variation have been shown. In the consideration of these specifications, a number of

CHART I.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency, or power to sustain clear seeing. Ratio time clear to time blurred is plotted against length of test period.

Reflector	Volts	Foot-candles		
		Horizontal	Vertical	45°
Type I	111	4.1	1.14	2.7
Type II	110	3.7	1.13	2.6
Type III	107.5	4.2	1.16	2.6
Type IV	105.5	3.8	1.15	2.5
Type V	105.5	3.7	1.15	2.6
Type VI	107.5	4.2	1.16	2.7



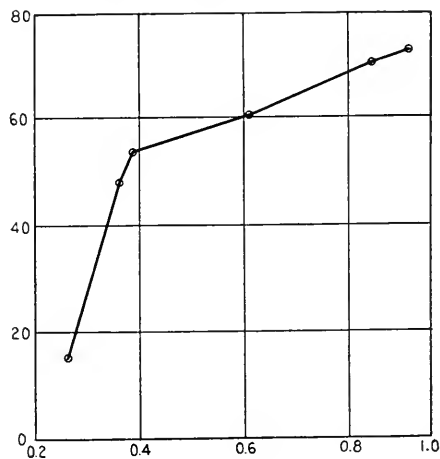
single items might be selected as of possible significance in relation to the effect on the eye. Among these may be mentioned the order of magnitude of the highest brilliancies; the average brilliancy; the ratio of the highest to the lowest order of brilliancy; the ratio of the highest order of brilliancy to the average bril-

liancy; the ratio of the average to the lowest order of brilliancy; the ratio of the highest order of brilliancy to the brilliancy at the point of work, (brightness of test card and reading page); etc. In order to see which of these correlate most closely with the results of the test for tendency to cause loss of efficiency,

CHART II.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency or power to sustain clear seeing. Percentage drop in ratio time clear to time blurred is plotted against brightness of reflector in candlepower per square inch.

Reflector	Volts	Foot-candles			Cp. per sq. in.
		Horizontal	Vertical	45°	
Type I	111	4.1	1.14	2.7	0.264
Type II	110	3.7	1.13	2.6	0.361
Type III	107.5	4.2	1.16	2.6	0.392
Type IV	105.5	3.8	1.15	2.5	0.614
Type V	105.5	3.7	1.15	2.6	0.848
Type VI	107.5	4.2	1.16	2.7	0.920



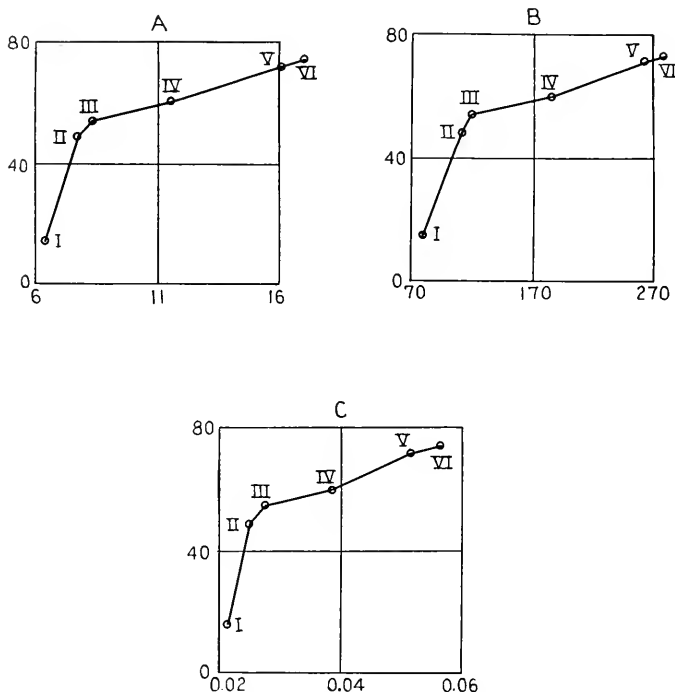
curves are constructed in which some of these features are plotted against the results of the test. These curves are given in Charts II to IV. In Chart II per cent. loss of efficiency is plotted against the highest order of brilliancy, namely, the brightness of the reflectors. In Chart III and IV are grouped the remainder of the curves.

Another method of evaluating the results of our test was briefly

treated of in a discussion of Mr. Cravath's paper by one of the writers. (The TRANSACTIONS, 1914, IX, pp. 1051-1053.) In this method the ratio of the time seen clear to the total time of the observation is taken as the measure of the ability of the eye

CHART III.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency or power to sustain clear seeing. In curve A percentage drop in ratio time clear to time blurred is plotted against ratio of average brightness to brightness at point of work; in B, against ratio of lightest surface to brightness at point of work; and in C, against average brightness.

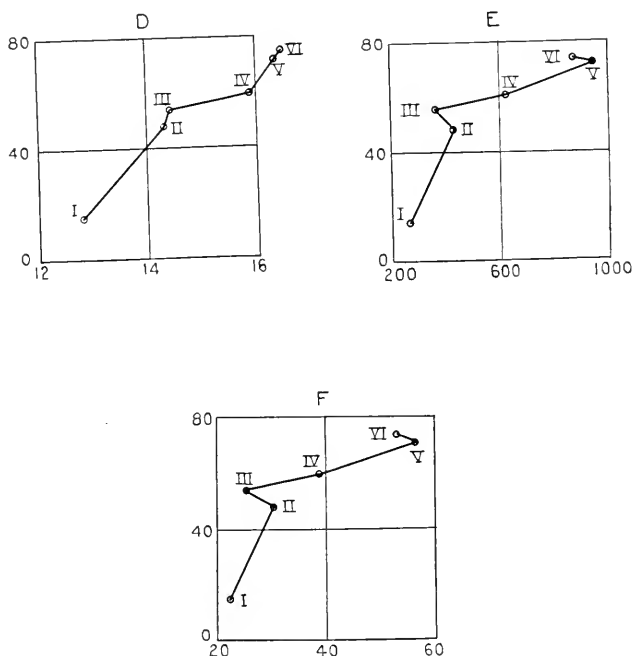


to sustain clear seeing at the time the test is taken. For the sake of comparing this method of evaluation with the one we have used in the rest of the paper, Charts V and VI have been constructed. In Chart V length of test period is plotted along the abscissa, and the ratio of time clear to total time of observation is plotted along the ordinate. In plotting these lines, one of the larger squares

along the abscissa represents one hour of the test period, and along the ordinate, O.I ratio, time seen clear to the total time of the observation. That is, in this method of treating the results, since the ratios, or the quantities to be plotted along the abscissa, are much smaller than they are in the former method, the scale

CHART IV.

Showing the tendency of the six types of reflector to cause loss of visual efficiency or power to sustain clear seeing. In curve D percentage drop in ratio time clear to time blurred is plotted against ratio of lightest surface to average brightness; in E, against ratio of lightest surface to darkest surface; and in F, against ratio of average brightness to darkest surface.



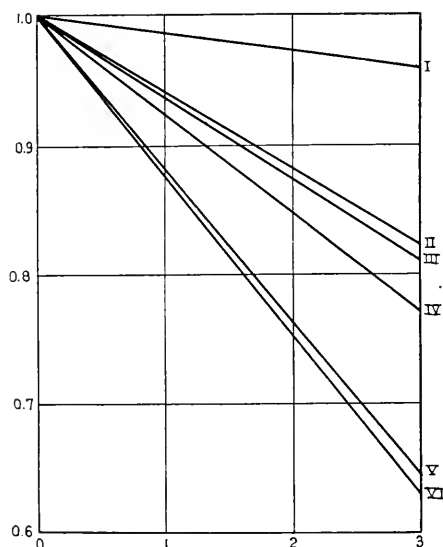
has been multiplied by 10 for convenience of representation. In order that the lines may all start at a common point, the initial ratios are reduced to 1 as a common standard. In Chart VI, per cent. loss of efficiency as evaluated by this method is plotted against intrinsic brilliancy of reflector. As before, intrinsic brilliancy of reflector is plotted along the abscissa, and per cent.

loss of efficiency along the ordinate. A comparison of these results with the former will show the same order of rating of the reflectors but a slight change in the position in the scale given to some of the reflectors. For the purpose of discovering what is

CHART V.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency or power to sustain clear seeing. Ratio of time clear to total time of observation is plotted against length of test period.

Reflector	Volts	Foot-candles		
		Horizontal	Vertical	45°
Type I	111	4.1	1.14	2.7
Type II	110	3.7	1.13	2.6
Type III	107.5	4.2	1.16	2.6
Type IV	105.5	3.8	1.15	2.5
Type V	105.5	3.7	1.15	2.6
Type VI	107.5	4.2	1.16	2.7



the best way of treating the results of the tests, several methods have been employed. Up to and including the present paper, however, only three of them have been given in print: ratio of time clear to time blurred, ratio of time clear to total time of

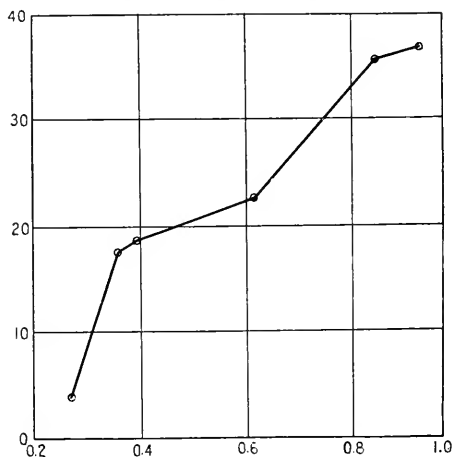
observation, and the per cent. of drop in the ratio time clear to time blurred. An ultimate decision with regard to what is the best method of treatment of the results can come, we believe, only with the consideration of a larger number of cases.

The work was concluded by determining for the six types of

CHART VI.

Showing the tendency of the six types of reflectors to cause loss of visual efficiency or power to sustain clear seeing. Percentage drop in ratio time clear to total time of observation is plotted against brightness of reflector in candlepower per square inch.

Reflector	Volts	Foot-candles			Cp. per sq. in.
		Horizontal	Vertical	45°	
Type I	111	4.1	1.14	2.7	0.264
Type II	110	3.7	1.13	2.6	0.361
Type III	107.5	4.2	1.16	2.6	0.392
Type IV	105.5	3.8	1.15	2.5	0.614
Type V	105.5	3.7	1.15	2.6	0.848
Type VI	107.5	4.2	1.16	2.7	0.920



installations the relative tendencies to produce ocular discomfort. As before, two cases were made of this determination,—one when the eye was at rest, the other when it was at work. For a description of how the determination is made, and a discussion of the method that is used, see the *TRANSACTIONS* of the I. E. S., 1913, VIII, pp. 54-58; and 1915, X, pp. 496-501. Space will be taken here only for presentation of the results. These are given

in Table X. In this table are given also, for the sake of comparison, results expressing the tendency of the six types of reflectors to cause loss of ability to sustain clear seeing.

APPENDIX.

The reflectors used in this work were supplied by the Holographane Works of the General Electric Co., and are opal glass of light, medium, and heavy densities. They are all of the bowl type and of the same size, 8 in. Reflector I is a pressed Sudan toned brown; reflector II, a blown white glass, toned brown (experimental); reflector III, a pressed Sudan; reflector IV, a pressed Druid; reflector V, a blown Veluria; and reflector VI, a blown white glass (experimental). Reflectors I, III, IV and V are commercial products, but II and VI are special, inserted in the series to give gradations in density. As was stated in the text these reflectors presented considerable unevenness of surface brightness. This was especially true of the pressed reflectors, which are smooth on the inside and grooved on the outside. The glass in these grooves being thinner than in the spaces between, a very uneven surface brilliancy is given to the reflector. Further, reflector IV, because of its imperfect diffusion, was quite a little brighter in the center, at the location of the filament, than at the top and bottom. In determining the brightness of these reflectors, overlapping readings were taken and an average obtained.

NOTES.

¹The truth of this should be obvious to any methodological critic. It is in fact the logical corollary of the application of a new test to a new field. Until a range of application is made which is reasonably representative of the work for which the test is designed to be used, a complete description of the test itself, including a statement of the factors which may influence its results and full directions how to use it, cannot possibly be given without more presumption than we care to exercise. While an attempt to do this might afford a certain amount of specious satisfaction to the practicing engineer, it would be superficial and incomplete and calculated to produce trouble in the work of others. When in the opinion of the authors a sufficient range of work has been covered, a separate paper will again be devoted to the test method itself in which data collected from all the work will be submitted, and the adaptability and application of the method to different kinds of work will be discussed. It is clear, we think, to anyone who has had experience in developing and applying a new test that this can be done more safely and effectively at the close of a section of the work which is sufficiently comprehensive to be representative of the accomplishment of the test, than at its beginning or while the work is yet in progress. In this later paper data will be submitted also on four types of test devised by us to detect changes in the functional condition of the retina as the result of working under different conditions of lighting.

Two points keep coming up, however, with a degree of persistence which may

justify a somewhat detailed discussion at this time. The first pertains to the sensitivity of the test to factors extraneous to the conditions that are being tested. The point was briefly discussed in the original paper on the test and again in the two succeeding papers. It was brought out more especially in Mr. Cravath's paper and in the discussions following it. Among other things it was shown in this paper that by purposely varying these factors in some extreme way they could be made to influence the results of the test. The more crucial point was not shown however; namely, that they operate against the usefulness of the test when the work is done under the conditions that ordinarily obtain in a well conducted experiment; nor does the paper contain any evidence that Mr. Cravath thinks this is the case. In our own work a different plan has been pursued with regard to this point. Instead of trying to find out what effects could be produced by means of procedures that would not be permitted in making a test, every care has been taken from the beginning to eliminate or hold as constant as possible all extraneous factors which might influence the general and muscular efficiency of the eye, and to check up the effectiveness of this control by carefully determining the mean variation in the results for each set of lighting conditions. This we have considered to be the most direct and feasible plan of conducting the work. In any event, it is obvious that there is no need of futile speculation concerning the possibilities of influence of these factors, nor of any indefiniteness either in the discussion or investigation of the point, so long as the actual value of the influence can be measured by determining the mean variation and its relative value be estimated by comparing the mean variation with the variations produced by changing the conditions to be tested. That is, a measure of the absolute and relative value of these factors is readily available and this measure has been carefully used at every step in the work. We need scarcely to point out that it is a well recognized principle of experimentation in comparative work such as we are doing that as long as the mean variation is safely within the experimental variation, the method is considered satisfactory for the purpose for which it is being used.

In this connection it may not be out of place to give here a more detailed account than has yet been given of the method that has been used in selecting and training observers. Care is exercised in the first place to choose one who has shown a satisfactory degree of precision in threshold and equality judgments in other optical work in the laboratory, and whose clinical record shows no uncorrected defects of consequence. The observer is then practised on the three minute record under a lighting condition selected and maintained for the purpose, until a satisfactory degree of reproducibility is shown. These records are usually run in series of five with a twenty minute rest interval between each record. So far we have not published the results of an observer who has not been able to attain a reproducibility in the time seen clear of 1 per cent. for a series of five records in these preliminary experiments, although this degree of precision is unnecessary unless the observer is being trained for work in which there are very small differences in the conditions to be tested. Since these records are run with no change in the lighting conditions and with rest intervals to prevent general or optical fatigue, they serve primarily as a training in making the judgment and as a check on the precision of the judgment. In the second stage of preparation the observer makes a number of three hour tests with records before and after work for two or more lighting installations, and the mean variation of the results from the average is determined. Again, if a sufficiently small mean variation is not shown where there has been no change in the lighting conditions, the observer is not allowed to take part in the actual work of testing. This last mean variation is the final preliminary check upon all the factors that may vary under the control imposed,—lack of reproducibility in the judgment, variable physical and mental fatigue, etc. The final check is had in the course of the work itself. That is, a number of tests are made for each lighting condition of the series to be investigated, and the mean variation is determined for each and compared with the variations that are produced by the changes in the conditions to be tested, to find out to what extent these variations may be ascribed to the changes made and to what extent to the normal variation of the test. How much larger is the variation which is produced by changing the lighting conditions than is the normal variation for each condition may

be seen by comparing Columns 14 and 15 of Table IX. In the work of the preceding papers the excess of the experimental variation over the mean variation was much greater still as might be expected from the greater differences that were present in the lighting conditions tested. For example, in five three hour tests for the indirect system for Position I (see this TRANSACTIONS 1915, X, pp. 413-426) the mean variation in per cent. was 1.1; for the semi-indirect system it was 1.4; and for the direct system, 1.2; while the percentage drop in the ratio from beginning to close of work for these systems was respectively, 8.5, 72.3, and 80.9. Similar citations may be made for the other conditions tested. When one compares in these cases the mean variation with the magnitude of change of ratio produced by changing the lighting system, it becomes obvious how unnecessary has been the concern about the influence of extraneous factors in case of the work that has as yet been done. In fact, the mean variation has been so safely within the experimental variation that the writers have not felt it necessary heretofore to make the numerical comparison in print. It is so well recognized as an experimental principle that the experimental variation shall safely exceed the mean variation that it has been their custom to give the comparison only when there exists some grounds for doubt. Heretofore, we have, as a general case, been working with conditions that produced a large difference in results.

As bearing on another phase of the question of reproducibility, namely, where a long interval has elapsed between two series of tests, we may cite one example where two series were taken under the same lighting conditions a year apart, and the variation in the average per cent. loss of efficiency was only 0.3. In this case a favorable lighting system was used, the initial ratios were closely the same, and the control in general good, although no especial care was taken to make it so more than what is ordinarily exercised. It is not presented, however, as a typical instance. It happens to be the only case of which we have a record, where a long interval has elapsed between two tests.

Moreover, there is nothing in the nature of the test other than its superior sensitivity that should make it more susceptible to the influence of extraneous factors than any other test of acuity. The principle of the test will be remembered from the earlier papers. It is merely the conventional acuity test subjected to certain features of standardization for the sake of greater reproducibility, and made into an endurance test to give it additional sensitivity. The older test had not been found to be sufficiently sensitive to fatigue conditions to warrant adoption in our work. This test is in fact not meant to be a fatigue test. It was designed to test the dioptric condition of the eye, and may be used with more or less success as a test of how far a given lighting condition is conducive to clear seeing with a *maximum of momentary effort*; but it has not the essentials of a fatigue test nor of its converse, the ease with which clearness of seeing is attained,—which is what is needed primarily for the selection of lighting conditions for the greater part of the work that we are ordinarily called upon to do. Almost if not quite as good results, for example, may be gotten with it after work as before, when there is every other reason to believe the eye has suffered considerable depression in functional power. The reason for this is obvious. Although greatly fatigued, the eye can, under the spur of the test, be whipped up to give almost if not quite as good results as the non-fatigued organ when only a momentary effort is required. (See Column 8, Table IX, and former papers.) If fatigued, however, it can not be expected to sustain this extra effort for a period of time. The demonstration of this fact led early in our work to the introduction of the time element into the test. The principle involved is not a new one. It is merely the application of a very old and well known one to the work of testing for optical fatigue. If, for example, a sensitive test is wanted for the detection of fatigue in a muscle, as good results can not be expected if the test requires only a momentary effort on the part of the muscle as would be attained if the endurance of the muscle were taken into account. For our purpose, therefore, the old acuity test has been made into an endurance test, in which the fatigue or loss of functional efficiency of the eye is measured by its power to sustain clear seeing for a period of time. As such it should and does show a sensitivity for detecting fatigue far beyond what can be attained by the older and more established test when it is used

for that purpose. And being a test which is more sensitive to functional changes in the eye, it doubtless does show in some proportion to its greater sensitivity more effect of the indirect as well as of the direct factors that influence acuity; but since the indirect factors can be subjected to control, while the direct factors are varied, there is in proportion to the sensitivity of the test and the control exercised a gain for the purpose for which the test is used. That this gain is great is shown in all our work by a comparison of the size of the mean variation with that of the variation produced by the change in the conditions to be tested.

The second point we wish to discuss here refers to the part played in our experiments by a factor known among psychophysicists as the error of expectation. The belief that there is a need to take account of this error in sense judgments arises from the difficulty in keeping the observer in ignorance of the test material and of a certain amount of the experimental procedure. In our experiments there are just two points on which the observer has knowledge: namely, the test object and the lighting conditions or system under which the work is done. All the rest is kept concealed from him unless the experimenter should in turn serve as observer in which case his results are checked up by those of observers who have not served as experimenter. We will consider this factor first in relation to the test object. The observer knows what the test object is (the letters *li* in 8 point type) and is told to record, for example, when the dot is seen separate from the vertical line in the letter *i*. The question at issue then is whether proper account is taken in our experimental procedure of the influence of expectation on this judgment. The question can be discussed the most comprehensively perhaps by first considering rather broadly the status and development of experimental method with regard to this factor. As we have already intimated, the probable influence of expectation is an inherent difficulty in all sense judgments,—photometric, acuity, threshold, etc. That it can not be entirely eliminated is, we think, generally conceded as axiomatic. Psychophysicists have, therefore, turned their attention to attempts to compensate for it, and a need has been felt to do this in most cases only when the work requires that the determination be made with a great deal of precision. Different methods may be employed for this purpose all of which are more or less open to question. The one most frequently used perhaps, is the method of ascending and descending series. From a consideration of this method an idea may be had in a general way of all the methods of its class. Rather than to eliminate or even to lessen the operation of the factor, the purpose of this method is to control its direction and to plan the experiment in opposing series, so as to compensate for its influence in the final result. That is, in making a threshold determination, for example, the series in one case is begun below the threshold, and the observer is told that the stimulus will be increased until the threshold is reached; in the other case the procedure is reversed. For the final result an average is taken of the values so determined on the assumption that expectation in the two cases will influence the determination by equal amounts in opposite directions. Much has been said in the literature of psychophysics with regard to whether this method accomplishes what it is intended to accomplish, and more might be said; but it is immaterial for our purpose whether it does or not, for it is obvious that it could not be applied to our 3 minute records, for here the image to be judged rises to the threshold of discrimination independently of the control of either the observer or the experimenter. The individual judgments, therefore, could not be arranged in opposing series for the purpose of compensation. An entirely different type of method is to use an objective check on the judgment of the observer, and by this means endeavor to weed out from the results the influence of subjective factors. We tried for several months to devise a means of changing the stimulus in such a way that an objective check could be had on the registration of the observer without sacrificing the principle of the test. Such a change, however, could not be made in the test object which did not at the same time permit the eye to relax its strain at the instant of change, which it is obvious destroys the very feature which gives the test its superior sensitivity. The attempt to get an objective check, however, was made more for the sake of offsetting possible criticism than it was because of any belief that it was necessary for the purpose for which the test has so far been used;

for, as we have already stated, a determination of the mean variation for the 3 minute record, each one of which consists of a number of separate judgments, had shown us that the influence of expectation as a source of variable error is of negligible consequence. That is, the mean variation is the measure of the aggregate effect of all the variable factors including expectation, if indeed it be a source of error in the case under consideration, and it was found to be too small as compared with the variations produced by the changes in the conditions tested to be the cause for any concern for the purpose of the work. Moreover, it will be remembered that a knowledge of the test object is given to the observer as one of three changes that were made in the conventional acuity test to minimize very obvious sources of variable error, among which were memory and expectation, and to give a greater reproducibility to the judgment. We can do no better probably than quote from the original discussion. "Visual acuity tests of the Snellen type, especially when used in work in which it is required to make successive tests on the same person, are open to the following objections. (a) The judgment is in terms of recognition. A letter may be recognized when it is not seen clearly. In any judgment based on the recognition of even a single letter, memory plays an important role. It is, so far as the writer knows, impossible to standardize this memory factor and to obtain results strictly in terms of acuteness of vision. (b) The test card is made up of quite a long series of letters. As the test progresses the letters are memorized more and more completely. It is practically impossible to eliminate this progressive error when a number of successive judgments have to be made as is the case before a final result is reached in any single visual acuity test and as is especially the case when a number of successive tests have to be given to the same person, which happens in much of the work involved in the solution of the problem here proposed (c) The Snellen series contains quite a large number of letters. The eye is found to fatigue and vision to blur before the series is completed. This introduces an error which it is practically impossible to render constant." All of the above errors were eliminated, or at least minimized, in the tests finally adopted by us by changing the type of judgment and by adopting a simple test object, made up of only two characters, the letters li in 8 pt. type. In this test the observer's acuity of vision is determined by the distance at which he can just clearly distinguish the two test objects. In practise it has come to be a matter of distinguishing whether or not the dot is separated from the vertical line in the image of the letter i. The results are thus rendered directly in terms of acuity of vision and the progressive errors due to memory and expectation are minimized. In this regard the significance of the change in the type of judgment from recognition to the judgment of the separateness of two simple objects, *e. g.*, the dot and the line in the letter i, should not be overlooked. When the criterion is recognition and the task set for the observer is merely to identify the test object with its name or some memory of it from past experience, as is the case in the old form of the test, memory and expectation play their maximum role. Any extraneous clue or a partial discrimination of the object may in fact serve as a basis for all that is required in the judgment. When, however, the task set for the observer is a different one and he is required to judge the presence or absence of a space between the dot and line in the letter i, the role of these factors is reduced to a minimum, and the task is narrowed down to the judgment of a space threshold, one of the simplest and most reproducible types of sense judgment. In short then, a knowledge of the test object is given to the observer as a part of the modification of the conventional acuity test to minimize the effect of variable factors, among which memory and expectation play the chief role. And that it has accomplished its purpose is abundantly attested by a comparison of the size of the mean variation given by the test so revised as compared with that given by the older form. We may add that the letter l is used in connection with the letter i for two reasons. (1) A steadier fixation is given than can be attained by so small an object as the letter i; and (2) a standard is afforded (an unbroken vertical line) in terms of which to judge the separateness of the dot from the vertical line in the letter i.

The only other way in which expectation can come into the experiment through knowledge on the part of the observer is, as we have already stated, through an

awareness of the conditions or lighting system tested. The observer can not work for three hours under a given lighting installation without being more or less aware that the same installation is being used as was used before, or a different one. Moreover, we do not see how this unfortunate factor can be completely eliminated unless imbeciles be used for observers. We wish to point out, however, that there is no greater liability to harmful influences from this factor in our test than in the older acuity test or any other that could be applied to the same type of work. We grant that, in any test that could be used, if observers of strong commercial or other bias should in two isolated trials get better results for one type of lighting than another, there might be grounds for suspecting that prejudiced observations were made: but if each condition were tested a number of times, as has been the case in all of our work, and a small mean variation were obtained for each series of tests, the result would look much more like the response of an organism to a constant set of conditions in obedience to physiological law than it would like a voluntary reproduction guided by prejudice, however strong and constant that prejudice might be. Here again the size of the mean variation is the check upon the validity of the results, for it is obvious, we think, even to a novice, that records taken at intervals of from one to five days could not show a close reproduction if the fidelity of the registration were in any way interfered with by the wishes or prejudice of the observer. Furthermore, it is only fair to say that it would be difficult to find a group of observers freer from a direct interest in lighting conditions or a knowledge of their significance than is the group from which the greater number of our observers are selected.

² These factors are the evenness of illumination, the evenness of surface brightness, the diffuseness of light, the angle at which the light falls on the work, intensity, and quality.

³ The problem of installing is probably not the same for the inverted translucent as for the inverted opaque reflectors. In the latter case the height should be so adjusted as to give as nearly as possible an even distribution of surface brightness on the ceiling, and evenness of illumination on the working plane. In case the inverted translucent reflectors, however, if the distance from the ceiling is made great enough in all cases to produce these effects, it may throw the bright reflectors too low in the field of vision for the highest efficiency and the greatest comfort to the eye. In this regard the opaque reflectors have the advantage that it is always easier with them to get the brightest surface in the room out of the zone of most harmful influence in the field of vision. In later work we expect to conduct a series of experiments with the above reflectors in which the height from the ceiling is the factor varied.

⁴ The track along which the test card was moved was parallel to the east and west walls of the room. When taking the test the observer faced the north wall in such a position that when the eyes were in the primary position the lines of regard were parallel with the east and west walls of the room, and approximately normal to the north and south walls. That is, the head was erect and held in such a position that the objects in the room, reflectors, etc., fell as symmetrically as was possible within the field of view. During the three hours of reading which intervened between the two three minute records, the observer moved just far enough back from the upright supporting the mouth board to give room for the book to be held, and to permit of a comfortable reading position. Care was taken to have the eyes sustain as nearly as was possible the same general relations to the objects of the room as were sustained when the three minute records were taken. This could be done either by holding the head erect, etc., or by tilting slightly backward in the swivel chair used by the observer and allowing the head to relax a compensating amount. So far as the direct optical effects are concerned, it would seem to be immaterial which of these positions is chosen, so long as approximately the same field of vision is obtained. The latter is usually preferred by the observer as causing less general fatigue. When taking this position, the book is elevated and held at ap-

proximately an angle of 45° (a little nearer to the vertical than this perhaps). The brightness measurements of the book at this angle and in the horizontal are not taken, however, so much because of this as to give the brightness of the book in two fixed representative positions at the point of work. Care is taken to have print of uniform size and distinctness for use with the three systems and to have a page which gives a comparatively small amount of specular reflection. Uniformity in these regards can usually be secured by using numbers of the same journal.

⁵ It should not be needful to mention that the recording apparatus is screened from the observer's view while the test is being made. Before photographing, the screen was removed and the apparatus regroped.

⁶ This is the test station shown in Fig. 1, and of the four used in the former work is the one nearest to the south wall of the room.

⁷ As has been stated in our former papers, in the consideration of the effect of a given lighting situation on the ability of the eye to hold its efficiency for a period of work, the age of the observer and the condition of his eyes should be taken into account. All of the observers who have been employed by us in this work have been under 28 years of age. Following is the clinic report of the eyes of the observer whose results are given in Tables IX and X, made by Dr. Wm. Campbell Posey of Philadelphia.

Observer R.

With glasses.—Vision of right eye = 20/25. Far muscle test = $Q \frac{1}{2}$ esophoria.

Vision of left eye = 20/20. Near muscle test = orthophoria.

Ophthalmoscopic examination.—Right eye = mixed astigmatism, $\frac{1}{2}$ diopter.

Left eye = hyperopic astigmatism, $1\frac{1}{2}$ diopters.

External condition.—Adduction good; eyes slightly divergent under cover; cornea clear; pupils, $2\frac{1}{2}$ mm.; irides respond equally and freely to light, accommodation, and convergence stimuli.

Glasses worn during test.—Right eye = —S., 0.50 D.; —C., 0.37 D., $\times 160^\circ$

Left eye = —C., 0.50 D., $\times 180^\circ$

Early in our work the problem arose whether the three minute records before and after work should be taken in the same room in which the work was done or in a separate room reserved solely for that purpose. To test this point, work was done in both ways. It was found that the effects of smaller differences in lighting conditions could be detected when both the three minute records and the work were done under the lighting conditions to be tested. That is, the total test procedure, which includes both the three minute records and the reading, is more sensitive when it is all done under the conditions to be tested, than when a part of it is done under these conditions and a part in a separate room. Since the method is more sensitive when the whole procedure is conducted under the lighting conditions to be tested, we can see no reason why even the purist should demand that a part of it be done under the conditions to be tested and a part somewhere else, so long as the results are recognized to be the consequence both of the three minute records and of the reading. Our purpose, it will be remembered, has been to get a sensitive means of detecting the relative tendencies of different lighting conditions to cause a loss in the power of the eye to sustain its ability to see clearly; and the method is more sensitive when the three minute records, also, are made under the conditions to be tested. This, we may say, is our chief reason for the practice. A justification, we believe, is not logically needed. Moreover, the method so conducted is just as amenable to control and to checks upon its reproducibility, as if it were used in the less sensitive form. It is, in fact, considerably more amenable to control, for if a separate room were used for the three minute records, very great care would have to be exercised to see that it was always illuminated with exactly the same intensity of light that was used in the room in which the reading was done. If the illumination were not accurately the same, a period of adaptation would have to be allowed before the three minute record could be made, which, in case of the record taken after work, would give the eye opportunity to recover from the fatigue induced by

the work. It is obvious that a great deal of difficulty would be encountered in accurately maintaining this control; and, if it were not so maintained, an error of considerable consequence would be introduced into the work. In getting control not only the illumination of the test object must be taken into account, but the brightness of the whole field of vision with its complex distribution of light and shade, for this conditions the state of adaptation of the paracentral and peripheral portions of the retina which in turn exerts an influence on the part of the retina that receives the image of the test object. It may be added also that adaptation effects in the paracentral and peripheral portions of the retina are stronger and more rapid than in the central portions.

In connection with the fact that the three minute records add sensitivity to the method when they are also taken under the conditions to be tested, we may say that we are now working on a short method in which three minute records with proper rest intervals are used. This test is rougher and less sensitive than the longer method, but if it can be made satisfactory, it might be more adaptable to practical work.

⁸ It will be noted in this table that there is very little variation in the value of the initial ratios. We noted in each of our preceding papers and again in our discussion of Mr. Cravath's paper that the sensitivity of the test varies with the ratio of the working distance of the test object from the observer to the acuity distance. After considerable investigation of the point, we adopted, as a standard to be attained approximately, a ratio of distances that would give for the initial record a ratio of time clear to time blurred of 3.5. As might be expected, it is impossible to get this ratio of 3.5 exactly from any single ratio of working distance to acuity distance that can be determined in advance of the actual record. But with care a close approximation may be attained, and since the loss of efficiency is judged from the amount this ratio is changed from the beginning to the close of work, and not from the ratio itself, the failure to obtain it does not affect a comparison of the favorableness of different lighting conditions for the eye, any more than is represented by its effect on the sensitivity of the test. In short, the variations in this ratio from test to test form merely one of the group of variable factors, the check upon the effect of which on the results of the test, is the size of the mean variation; and, so long as this mean variation is safely within the amount of variation produced by changing the conditions to be tested, the control may be considered as satisfactory for the purpose of the work that is being done. That is, when this check is properly exercised, the influence of a variation in this ratio can not possibly be mistaken for the effect of the condition which is being tested. However, in the course of the determination of what value of initial ratio should be used, considerable study was made of the effect of varying the ratio. While space will not permit us to quote largely from these results here, still an idea may be given in the space at our command, of the order of magnitude of the effect that is produced. That is, we will take three cases including a range of differences amply great to cover what is ever apt to occur in actual work. In the first, the initial ratios were 2. and 3. (difference, 1); in the second, 2.67 and 5 (difference, 2.33); and in the third, 1.93 and 7.57 (difference, 5.64). The difference in the percentage loss of efficiency for the first case was 1.4; in the second, 2; and in the third, 1.7. The effect shown in these cases, it will be observed, is about of the same order as the normal mean variation of the test.

⁹ In order to make a fair comparison between the drop in ratio time clear to time blurred caused by working under a given lighting condition and the mean variation of the drop, the percentage drop and the percentage mean variation are both estimated in the above table, also in the citation made in Note 8, p. 1129, on the same base, 3.5. If this comparison had not been wanted especially to show that the mean variation produced by changing the type of reflector, it would have been more in accord with custom perhaps to have expressed the mean variation as a percent. of the mean value of the drop. Computed in this way the value of the mean variation for Reflectors I-VI would have been in order 5.6 per cent., 1.6 per cent., 1.3 per cent., 3.3 per cent., 1.2 per cent., 1.4 per cent.; and for the citation in Note 8, they

would have been for the indirect system 4.5 per cent., for the semi-indirect system 0.7 per cent., and for the direct system 0.5 per cent. This method of estimating the mean variation gives, it will be noted, the largest per cent. variation for the most favorable lighting condition because the drop in ratio, the base on which the percentage is estimated, is the smallest for this condition. The actual variation we have found as a rule is, as might be expected, the least for the most favorable condition.

DISCUSSION.

MR. J. R. CRAVATH: Dr. Ferree calls his test a test "loss of efficiency of the eye." I think the term "eye-fatigue" is much briefer and more expressive. The work reported in a previous paper of Dr. Ferree covered conditions rather widely varied. The paper we have before us now covers conditions which come within fairly narrow limits of visible source brightness. The results have been especially interesting to me as a member of the Committee on Glare because we have, during the past year, attempted to formulate or to express certain limits of good practise which are least conducive to glare. In ordinary interior illumination, we state in our report, which is soon to be published, that contrasts of brightness of adjacent surfaces (I mean by adjacent surfaces, those which are adjacent within the visual field) should not be over a ratio of one to two hundred, and preferably not over one to one hundred. That ratio was taken as the result of an examination of a good deal of data, some of

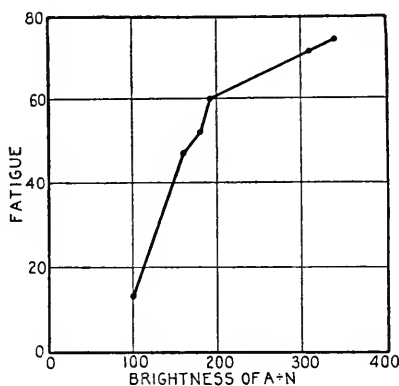


Fig. 1.

them in previous papers of Dr. Ferree. It was therefore of considerable interest to me to see how the results in the present paper

conform with these limits and in order to do that, I have taken the ratio between the brightest spot, which of course, is the reflector, and the point N on the room photograph a little to the right of the reflector, and plotted a curve, Fig. 1, corresponding to Chart II but, instead of using the brightness of the reflector, I have used the ratio of the brightness of the reflector to the darkest point along side of it; that is the point N. The ratios of A to N under 200 seem to give notably less fatigue than those above 1 to 200, which would confirm the judgment of our committee as well as the previous results obtained from various sources.

DR. J. W. SCHERESCHEWSKY: I want to congratulate Dr. Ferree on the extreme care which is evident in all these series of tests to obtain small mean deviations and secure reproducibility of results. I wish to call attention, however, to one factor, which in all probability, will have considerable effect on all tests which involve muscular action and that is the question of weather conditions. It is plain to all who have read this paper that tests of this kind such as Dr. Ferree has here published are labors requiring a great deal of care in arranging and carrying out, and it seems to me that we ought, by all means, in working tests of this character, to insure, as much as possible that the work shall not be thrown away because of great variations in the results due to extraneous factors. Now it seems to me that tests of this kind ought never to be conducted in very hot weather. The effect of high degrees of heat and humidity is to reduce the endurance of muscle. That seems to be plain from Prof. F. Lee's experiments which were done in the investigations of the New York Ventilation Commission, in which it was found that sections of muscles removed from animals which had been subjected to high degrees of temperature and humidity furnished on the average 40 to 50 per cent. less contractions than muscles of animals which had not been so exposed. Therefore, it seems to me that persons who conduct tests of this kind in very hot weather would find a great loss of efficiency of the eye simply from exposure to weather conditions; so in the future, when we are endeavoring to corroborate the results of these tests by similar tests, we must take the precaution never to undertake such tests except when the atmospheric conditions are distinctly comfortable.

MR. T. W. ROLPH: The data given in this paper are very valuable to us who have lighting systems to design.

I should like to call attention to the ratio between the brilliancy of the ceiling and brilliancy of the reflectors as obtained in these measurements. Reflectors 4 and 5 are typical reflectors of the class which is most commonly used to-day for semi-indirect lighting, and in this particular installation, which does not represent all installations, but is possibly a typical installation, the ratio between the brilliancy of the reflector and the brilliancy of the ceiling is one to fifty, and with reflector 5, one to sixty-one, taking the brightest point on the ceiling. Those are the reflectors which show the greatest eye fatigue, and this shows us how far we will still have to go in reducing intrinsic brilliancy in order to get semi-indirect lighting systems which are correct from the engineering standpoint. Now, reflector No. 3 is a commercial reflector which is being used to a certain extent for semi-indirect lighting. It is denser glass and it is harder to sell than reflectors 4 and 5, so that we who are working for better lighting in the commercial field have that to contend with. Reflector 3 shows a ratio between the brilliancy of the ceiling and the brilliancy of the reflector of one to sixteen. The densest reflector tested has a ratio of one to nine. Three years ago, in a paper on the "Engineering Principles of Semi-Indirect Lighting," I argued that, from the engineering standpoint, the brilliancy of the reflector in an installation should be approximately the same as the brilliancy of the ceiling. That was not particularly from the standpoint of eye protection, but from the standpoint of obtaining the maximum diffusion of illumination, arguing that if we are going to sacrifice the efficiency of direct lighting by installing semi-indirect systems, we should try to get the maximum engineering value of the semi-indirect systems, by obtaining maximum diffusion, and that this would be obtained when the brilliancy of the bowl is approximately the same as the brilliancy of the ceiling. This paper indicates that to obtain good eye-protection in semi-indirect lighting, we should work to very much denser glassware or very much lower brilliancy of reflector bowl than is generally practised to-day. Even a ratio of one to nine, where the reflector is nine times as bright as the ceiling, shows a considerable degree of eye fatigue.

There is one point I should like to bring out in connection with the measurement of the intrinsic brilliancy of these reflectors, and that is merely a suggestion that possibly a good way to obtain the intrinsic brilliancy of a reflector of this character would be to take the candlepower as determined on the photometer, and the area of the reflector as determined on a drawing board, and thus find the candlepower per square inch, rather than to take luminosity measurements of the reflector at various points and average them. I believe it would be more accurate to take the candlepower of the reflector and simply divide it by the projected area in the direction of view.

MR. J. R. CRAVATH: This question of what shall be taken as the criterion of brightness is something that Dr. Ferree evidently is not sure of, and I don't think any of the rest of us are—I mean, what particular contrast shall be taken. Mr. Rolph has just mentioned the contrast of the brightness of the reflector with the brightness of the ceiling above. Dr. Ferree has given us results showing the highest brilliancy, that is, the brilliancy of the reflector, and the average brilliancy, and the ratio of the highest to the lowest and the ratio of the highest to the average, the ratio of the average to the lowest and the ratio of the highest to the brilliancy of the point of work. There is such a great deal to be said in favor of his objection that, possibly, in a case where the subject is working continuously on desk work or reading that the ratio of the brightest object in view to the work, that is, to the paper on which the eye is working, should be the criterion; because in that case, the brightest objects in view appear simply on the edge of the retina most of the time, while the paper is on the center; but for most practical purposes, I think perhaps the criterion adopted by the Committee on Glare of the ratio between the nearest adjacent surfaces would answer all practical purposes for the present. I also want to express the debt that I feel the practical men of the society owe to the investigators who bring out this kind of data; it is exactly what we need to make progress in our work.

DR. C. E. FERREE (In reply): I suggested in a former paper that, theoretically considered, better results should be gotten with the semi-indirect reflector of such a density as to give a surface brilliancy equal to that of the ceiling spot than are obtained with

the totally indirect reflector. That is, if the reflector is made of the same brightness as the ceiling spot, the same light flux can be obtained with a lower intrinsic brilliancy of the brightest surface than if the light all comes from the ceiling spot because of the increase of luminous area. This is in agreement, I believe, with the general tenor of Mr. Rolph's discussion. Unfortunately, however, I have not yet been able to obtain reflectors of sufficient density to test the point directly. However, in the work that we have done, an increase in the density of the reflector, so far as we have been able to carry the increase with the reflectors supplied us for the purpose, has been accompanied by a consistent improvement in the effect on the eye. There is one thing to be claimed, however, in favor of the indirect reflector when all is said and done. It is easier with it to remove the brightest spot in the field of vision from the zone of harmful influence to the eye, especially in rooms of the height ordinarily found in dwelling houses, because with this type of reflector the brightest spot is always on the ceiling. With reference to the effect of position or rather height of the brightest spot in the field of vision, it may not be out of place to anticipate here in slight measure the content of a future paper. In the work of the present paper the reflectors were installed 30 inches from the ceiling. This is in accord with general practise for the installation of totally indirect reflectors in rooms of the height of our test room and is considered to give a favorable distribution of light and shade on the ceiling and a comparatively even distribution of light on the working plane. So installed, however, the brightest spot (the reflector) is dropped well into the field of view, especially at the outlets most removed from the observer. The question arises, therefore, whether semi-indirect reflectors should be installed according to the principles of indirect lighting, direct lighting, or whether some compromise should be made between the two. We have begun, therefore, a series of tests in which the distance of the reflector from the ceiling is varied. So far we have been able to finish the comparison for the reflectors of least and greatest density at distances of 30 in. and 15 in. from the ceiling. The 15-in. distance gave quite considerable improvement in the effect on the eye for the reflector of least density, but not nearly so much for the reflector of greatest density. This result suggests that a more careful

study should be made of the method of installing semi-indirect reflectors differing in density. It would seem that the denser they are the more nearly they can afford to be installed as indirect reflectors and the less dense they are the more nearly they should be installed as direct reflectors so far as eye effects of the kind revealed by our tests are concerned.

I have no doubt that Dr. Schereschewsky is right about the probable effect of excessive temperature on the results of tests such as ours. I am very frank to confess, however, that I never do anything on a hot day if I can help it; and I certainly would not conduct a test when the temperature is excessively high. Through the greater part of the year the temperature of our test room is kept within a small variation by thermostat control. If it is necessary to work on warm days electric fans are used; but on no account are tests ever made on hot, humid days. In fact nearly as much care has been taken, I should say, to secure uniformity in temperature control in our work as has been taken to secure a uniform control of illumination and brightness effects. I am confident, therefore, that our results so far have not suffered from temperature as a variable factor. If I may digress here for a moment, I should like to say, with no reference whatever to Dr. Schereschewsky, whose discussions I have always found to be most considerate and intelligently liberal in tone, that I am becoming somewhat tired of the subject of extraneous factors. To speculate about their probable influence may be of considerable cultural value to those who have heretofore thought little about the subject, but there is no need to worry about their influence or to stand in the way of reasonable progress when a gauge on the amount of their influence may be and has been had at every step in the work. In this latter connection I refer to a careful determination of the mean or average variation. If this is done as it has been done at every step in the training of the observer; if moreover it is done for each condition tested and a comparison made of its amount with the amount of variation produced by changing the condition tested; exact knowledge is had in every case whether or not the results obtained are significant. The subject of gauging the influence of variable factors is too old and has been too carefully worked out to justify the raising in any

scientific body of as much elementary discussion as has been raised with regard to it in this Society. The procedure in general is very simple and straightforward. Train the observer on every feature of the test method with careful attention to the size of the mean variation. In the actual work determine the mean variation for each set of conditions tested and compare it with the variation produced by changing the conditions to be tested. If its sum for any two sets of conditions is not less than the difference between the average results obtained for the two conditions these results, it is usually considered, can not be claimed as significant. I have spent months, for example, in the training of an observer on the different features of the test method, only to discard him at the end of that time because a sufficient degree of precision of record could not be obtained under a constant set of lighting conditions. Those who have shown in such a course of training an unsatisfactory degree of precision usually reveal on examination, I may say, some uncorrected optical defect. Muscle imbalance more often than any other seems to have been the defect in the cases which have so far given us trouble. This may mean that the extrinsic more often than the intrinsic muscles are the cause of a variable performance on the part of the eye in tasks such as we have set for it in our tests, but it is also probable that the occurrence is due to a considerable extent to the fact that in ophthalmological practise small defects in muscle balance are more often left uncorrected than are, for example, refraction defects.

In concluding my comments on this point I think I may be justified in mentioning that I have spent a greater number of years than I like to recall in trying to get control of the variable factors that influence the response of the eye; and that I have added considerably to the precision of its performance under experimental conditions, I can only call upon my published work to testify. It is not likely, therefore, that in the course of developing a new test I would show such a degree of incaution with regard to the most elementary and well-known principles of experimentation as was made the subject of serious and somewhat pretentious inquiry in the discussions of the paper preceding the present one, and in the discussions aroused by Mr. Cravath's paper.

I am glad Mr. Cravath has given us still another way of plotting the results of the tests against brightness effects. It has not occurred to me, however, to attach any especial importance as a separate factor to the ratio of the brilliancy of the brightest area to that of its immediately contiguous surroundings. There are, for example, only two possible effects that I could conceive to be due to this relation, neither one of which would seem to me to warrant making of it a separate factor. (1) It would enhance by physiological induction in some proportion to the difference in physical brightness, the brightness of the sensation aroused by the reflector and thus increase its power to set up muscular strain by distracting the eye from the adjustment needed for the work in hand. So considered, however, its action would merely be that of an auxiliary factor, supplementary to the actual brightness of the reflector. As such it is of course of a great deal of importance, greater perhaps, for example, that the relation of lightest to darkest surface, as brightnesses are graded in a room ordinarily well illuminated. In short it would seem to me that the point of reference in determining the relations that are of importance to the eye is the brightness at the point of work. Any extreme deviation above or below this brightness, especially above, or anything that would make these deviations conspicuous to vision would seem to me to be of prime importance. I would, therefore, consider it an important addition to our present method of specifying brightness effects to give more detailed measurements, so far as is practicable, of the surroundings immediately contiguous to the brightest spot, because the effect of that spot upon sensation is to an important degree dependent upon the immediate surroundings; but I would by no means be willing to make these measurements and that of the brightest spot the sole specification of brightness effects, as Mr. Cravath suggests might be sufficient for our present needs. Moreover, it must not be overlooked in this connection that a curve plotted on a basis of the ratio of A , brightness of the reflector, to N for the different conditions tested must give a curve very similar to that plotted on the basis of the brightness of the reflectors alone, for N does not vary greatly from a constant value for the six sets of reflectors we have used. Obviously, therefore, cognizance should be taken of this fact before too much general importance is attri-

buted to this ratio as a separate factor from the shape of the curve plotted by Mr. Cravath for this particular set of conditions. (2) There might, it is conceivable, be some unknown effect on the retina which directly depresses its functional power or indirectly disturbs the adjustment of the eye. I have, however, already tested quite extensively the tendency of different lighting conditions to depress the functional power of the retina for as much as ten hours of continuous work and have found reason to believe that very little indeed of our results for the tests for loss of efficiency could be ascribed to a depression of retinal function. There are four ways, I may say, in which a change in the functional activity of the retina may be manifested: (a) a change in sensitivity to color and brightness; (b) a change in lag or the time required for the sensation to reach its maximum; (c) a change in the susceptibility to fatigue or exhaustion, measured by rate of exhaustion; and (d) a change in the power of recovery, measured by rate of recovery. All of these points were covered in the tests mentioned above. Short of such an investigation a complete record can not be given of the functional state of the retina at any time or as the result of any condition or set of conditions to which it may be subjected. But when such tests have been conducted for a period of exposure of the eye to the conditions tested more than three times as long as was used in the tests for loss of efficiency, it would seem reasonable to conclude that the results of this latter test could not be ascribed to any considerable extent to a depression of retinal activity.

Mr. Cravath has always quarreled with me over what the test should be called and perhaps on good grounds. If "fatigue" is a more palatable term to the engineer than "loss of efficiency," I am quite willing that the test shall be called a fatigue test. I have in fact called it that part of the time myself. My reason for calling it something else in the beginning was primarily one of profession. Among men in physiological and psychological optics the term fatigue as applied to the eye has been, since the days of Fechner and Helmholtz, a technical term connotating a retinal condition. It was chiefly to avoid the chance of confusion with the narrower usage of fatigue that I chose the broader term loss of efficiency as a brief designation of what is really tested, namely, the loss in the power of the eye to sustain clear seeing.

A NEW METHOD OF HETEROCHROMATIC PHOTOMETRY

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In a former paper¹ it was stated that a satisfactory method of photometry should combine the following features. (1) It should enable us to detect small differences in luminosity and to reproduce our results for a given observer with a small mean variation and for a number of observers with a comparatively small mean variation. That is, the method should possess an adequate degree of sensitivity, and should give results with a satisfactory degree of reproducibility.² (2) It should be known either to possess of itself logical sureness of principle or its results must agree in the average with those of some method which can be shown to possess this sureness of principle. Methods having these features have been developed for the photometry of colorless light. The problem for the photometry of colored light, however, has presented great difficulty.

The methods for the photometry of colored light may be grouped under two headings: the direct and the indirect methods. In the former class we have the method of direct

¹ Ferree, C. E. and Rand, Gertrude, 'A Preliminary Study of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Color,' *Psychol. Rev.*, 1915, 22, pp. 110-162.

² It is scarcely needful to point out in this connection that the method should give results with a satisfactory degree of reproducibility for observations separated both by short and by long intervals of time.

comparison or as it is sometimes called the equality of brightness method. This method is generally accredited with sureness of principle but it is deficient on the side of sensitivity and reproducibility when lights differing in color value are compared.¹ Of the latter class the method of flicker has received the greatest amount of attention and has been the most favored. But in our former paper it was shown (1) that the method of flicker, so far as it has been developed up to the present time, does not possess of itself the sureness of principle needed to meet the requirements of a satisfactory method; and (2) that as yet its results have not been found to agree on the average with those of any method which can be shown to have this sureness of principle. It was also stated that in a later paper a method of photometry would be described which possesses approximately as high a degree of sensitivity and of reproducibility as the method of flicker and gives results which agree very closely on the average with those obtained by the equality of brightness method, much more closely than results obtained by the method of flicker. It will be the purpose of this paper to give a brief description of this method. It was first used by the writers in connection with work in color sensitivity for the purpose of detecting small changes on the illumination of a room by daylight.² Although not so convenient perhaps as the equality of brightness method for many of the purposes for which photometry may be used, for this work the method did not present any great amount of difficulty, and it proved to be much more sensitive than the equality of brightness method. The equality of brightness photometers of the Sharp-Millar type, for example, are very insensitive for the determination of the illumination of a room by daylight, because the standard field

¹ *Loc. cit.*, pp. 114-115.

² See Ferree, C. E. and Rand, G., 'An Optics-Room and a Method of Standardizing Its Illumination,' *Psychol. Rev.*, 1912, 19, pp. 364-373; Rand, G., 'The Effect of Changes in the General Illumination of the Retina upon Its Sensitivity to Color,' *ibid.*, pp. 463-490; 'The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing,' *Psychol. Rev. Monog.*, 1913, 15, No. 62, pp. 79-166; see also Ferree, C. E., 'Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort,' *Trans. Ill. Eng. Soc.*, 1913, 8, p. 51.

illuminated by the tungsten lamp is deep orange in color, while the comparison field illuminated by daylight is clear white. This difference in color tone makes the judgment of equality of brightness difficult to make, and renders the instrument extremely insensitive for daylight work.

So far as the type of judgment is concerned, the method we are about to describe is in reality an equality of brightness method but it has the important advantage that the observer is never required to judge impressions differing in color quality. In making a photometric balance by this method, the feature is thus eliminated which has from the beginning of the work of measuring light intensities rendered the equality of brightness method difficult of application to heterochromatic photometry. Because of this factor we have at the suggestion of certain photometrists undertaken to work out the principle on which the method is based in a way that will be of general service to the work in heterochromatic photometry and to secure data on the points in terms of which a verdict is rendered for every method of photometry, namely, the sensitivity and precision of the method, and the agreement of its results with those obtained by the equality of brightness method.

The method is based upon the extreme sensitivity of the peripheral retina to brightness contrast, especially to the induction of black by a white screen. Not only is the peripheral retina extremely sensitive to brightness contrast, but, which is the crucial point of the method, very small changes in the illumination of the contrast screen produce a change in the amount of the contrast. That is, for any part of the retina, for example, the amount of contrast induced by the surrounding field upon a contrast stimulus increases with decrease of illumination. In the peripheral retina we have an extreme case of this. In this part of the retina very small changes of illumination indeed are required to produce a noticeable change in the amount of contrast induced, especially when the surrounding field is white and the stimulus is a gray of the proper brightness.

The apparatus needed for the method consists of a vertical

screen 60×50 cm. with an opening 15 mm. in diameter midway between top and bottom and 16 cm. from one edge, a motor to carry the measuring discs, and a photometer bar. The surface of the screen is covered with Hering mat white paper, or preferably with a paper overlaid with magnesium oxide deposited from the burning metal. This screen is graduated in the horizontal meridian from the center of the 15 mm. opening. Over the opening between the white covering and the screen is placed the gray which is to serve as the contrast-stimulus. Nos. 3-5 of the Hering series of standard gray papers were found to serve this purpose best for the intensities of light we used in the work the results of which are given in Table I. The measuring discs were made up of a sector of the same gray as was used for the contrast-stimulus and a sector of black, the varying proportions of which produce the match which is needed between the stimulus gray darkened by contrast and the measuring disc. The measuring disc was carried by a motor the shank of which is at one end of the screen and normal to it. When in position, the inner edge of the disc extends approximately to the 20° point of the graduations, and is about 3 cm. in front of the screen.¹ Immediately in front of the disc and 25° from the center of the stimulus-opening to the temporal side is placed the fixation-point.² The photometer bar was placed in a

¹ The measuring disc was placed this distance in front of the screen partly to give freedom of rotation but primarily to eliminate any induction by the screen on the disc. That induction is not present in any considerable amount under the conditions described above, is evident from the following considerations. (a) It is not directly detectable by the eye; and (b) a very high sensitivity is attainable by the method which could not be the case were induction present to any degree, for if it occurred in amounts great enough to influence sensation, the effect would obviously be to lower the sensitivity of the method. That there has been no lowering of sensitivity from this cause is rendered probable by the fact that approximately as small differences can be detected for lights differing in color quality as can be detected by Lummer-Brodhun photometers of the most improved type when the lights compared are of the same color quality.

² Care should be taken not to place the fixation-point so far from the stimulus-opening that the color used is seen of a different quality at this point than at the stimulus-opening. If this should occur for any color when the fixation is at the 25° point, a lesser excentricity should be chosen. The sensitivity of the contrast-effect to change of illumination is not lessened to any considerable extent, for example, by taking a 20° instead of a 25° fixation-point. We have found the 25° point to be very

plane normal to the screen midway between the stimulus-opening and the fixation-point. The contrast-stimulus and the measuring disc thus receive equal amounts of light from the source to be measured.

In Fig. 1 is given a picture of the apparatus in the rough form in which it is at present used. At *S* is shown the screen which is illuminated in turn by the standard and comparison lights; at *B* the photometer bar; at *D* the measuring disc; at *L* the lamp to be photometered; at *M* the mouthboard;

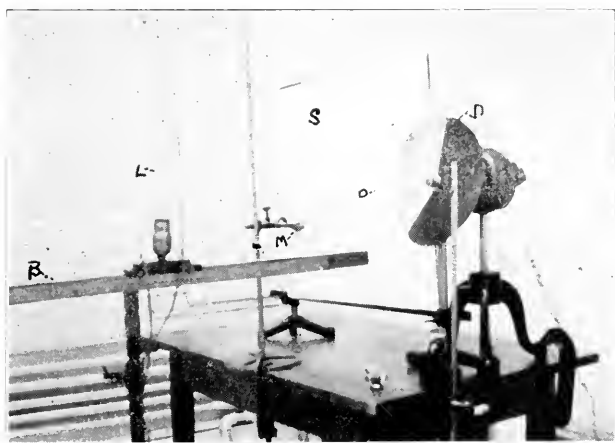


FIG. 1

and at *O* the opening filled with gray which is darkened in graded amounts by induction from the screen *S* as the amount of light received by it from the lamp *L* is varied. The screen *S* is supported by short rods screwed into heavy tripod bases. In order to provide for adjusting the height of the screen above the table the frame of the screen is fastened to the supporting rods by means of a collar and set screw. On the upper edge of this frame is attached a device for lining up the eye with the stimulus-opening *O*. This device consists of the following parts: A vertical arm carrying at its lower end a small circle 15 mm. in diameter extends satisfactory, however. For a fixation-point we used a black knot on a gray thread, stretched from a point on the screen *S* to a rod in front and on the opposite side of the measuring disc.

down to the level of the stimulus-opening *O*. Attached to the vertical arm just above this circle is a horizontal arm 15 cm. long which carries at its outer end and at right angles to it a disc 22.3 mm. in diameter. The size and position of the disc, the circle, and the opening *O* and their distances from each other sustain such relations that when the eye is in position 25 cm. in front of the opening *O*, the line of regard contains the centers of the opening *O*, of the circle, and of the disc; and the inner edge of the circle is just contained within the stimulus-opening; and the edge of the disc is just contained within the circle. That is, in effect the device is a peep-sight arrangement, and the alignment described above is possible only when the eye is in such a position that the line of regard is perpendicular to the stimulus-opening, the circle, and the disc at their centers. The device is attached to the metal frame by means of a screw with a milled head, so that after the alignment is made it can be readily turned out of the road and clamped. In order that the distance of the eye may be accurately adjusted at the same time its alignment is made with the stimulus-opening, a measuring device is also provided. This device consists of a slender brass rod 25 cm. long fitted at either end with two short right-angled arms 5 mm. in length. On the end of one of these arms is a ring which is just larger than the stimulus-opening, and on the other is a brass disc of the same diameter as the ring, provided at its center with a large pupillary aperture. In adjusting the distance of the eye this disc is rested lightly against the forward surface of the eyeball and the ring against the screen *S* concentric to the stimulus-opening. When the position of the eye is once determined, a mouthboard is adjusted and clamped in position so that the observer's teeth fit into impressions previously made and hardened in wax. This fixes the relation of the observer's eye to the stimulus-opening *O*. All that is needed, therefore, at subsequent sittings to bring the eye again into this relation, is to fit the teeth into the impressions on the mouthboard. As stated above, the photometer bar when adjusted stands in a plane normal to the screen *S* and midway between

the stimulus-opening and the fixation-point. This guarantees that the stimulus-opening and the measuring-disc at the fixation-point shall receive equal amounts of light from the lamp on the bar. The nearer end of the bar is placed at a distance below the level of the center of the stimulus-opening and fixation-point equal to the height of the center of the filament of the lamp above the bar. Owing to the fact that the head may cast a shadow on the stimulus-opening when the bar is horizontal, the rear end of the bar is raised until the stimulus-opening and the screen for some distance around are free from shadow for any position of the lamp on the bar that may be needed to obtain the photometric balance. In order to provide for this tilting, the bar is made adjustable in height. It is supported on two heavy tripod bases each carrying a vertical stem made of hollow tubing split at the upper end and provided with collar and set screw. Into these tubes fit rods attached to the photometer bar by means of hinge joints. This arrangement permits of an independent adjustment of the height of the two ends of the bar. In order that a given amount of slant may be reproduced at any subsequent observation, an attachment is provided to indicate the angle which the bar makes with the vertical. This consists of a graduated half circle attached just above the hinge joint to the supporting rod furthest from the screen. On this rod just below the hinge joint is fastened a pointer. When the further end of the rod is raised this half circle is rotated past the pointer and the amount of rotation may be directly read from its graduated limb. Since the angle at which the bar is tilted is kept the same for the comparison and standard lights, the tilting interferes in no way with the accuracy of the photometric balance or the application of the law of squares to the determination of the relative luminosities of the standard and comparison lights.¹

¹ We hope soon to use the principle upon which the method is based in connection with apparatus which will be more conveniently applicable to the general needs of the photometrist than is the rough device which is described above. One of the improvements which we expect to make, for example, is to eliminate the need of a slanting bar. For while the slanting bar does not interfere with the establishment of a correct photometric balance at the screen, it is not the most favorable condition under

The method is applied as follows: The observer's eye is lined up with the stimulus-opening in the manner described above and the contrast stimulus is put in position. The standard lamp is placed on the photometer bar at a given distance from the screen, the eye is turned out to the fixation-point and the sectors on the measuring disc situated just back of the fixation-point are adjusted by means of a number of separate judgments to match the gray at the stimulus-opening darkened by contrast.¹ The relative value of these sectors becomes the index of the illumination of the screen for the standard lamp at the given distance. The standard lamp is then removed, the comparison lamp is placed on the bar, and its position is adjusted

which to operate all types of lamps. This should not be difficult to do by moving the observer farther from the screen and using a correspondingly larger stimulus-opening and a greater linear distance from this opening to the fixation-point.

¹That is, with the change in the amount of light falling on the photometer head made up of gray stimulus and surrounding screen of white, there is a change in the amount by which the gray stimulus is darkened by contrast from the surrounding screen. This amount is recorded on the measuring disc directly behind the fixation-point, by adding a sector of black to the gray sector, which was chosen, it will be remembered, of the brightness of the gray stimulus uninfluenced by contrast. The value of this black sector thus becomes the fixed index of the amount of light falling on the screen in any given case. In short, with a given brightness relation of contrast stimulus to surrounding screen, there is a finely graduated scale of contrast values inversely correlative with the amounts of light falling on the screen. That is, with a large amount of light or high illumination of the screen, the amount of contrast induced is low; with a small amount of light falling on the screen the amount of contrast induced is high. The amount of change of the illumination of the screen needed to produce a noticeable change in the amount of contrast induced is very small indeed and because of this the method possesses a high degree of sensitivity. So far as we are able to determine, the amount of change in this illumination required to produce a just noticeable change in the contrast sensation is no greater than is needed to produce a just noticeable change in the positive sensation under the best conditions that have been as yet devised in photometric work for making the judgment, namely, the conditions presented by the Lummer-Brodhun photometer heads of the most improved type when the lights compared are the same in color quality. If this were not true, the method could not show, as it does, as great sensitivity for lights either the same or differing in color quality as does the equality of brightness method for lights of the same color quality. Also so far as we have been able to determine there is no greater variability in the eye's sensitivity to contrast from day to day than there is in its sensitivity to brightness itself. That is, photometric determinations by this method of a given light density on the screen show a very small mean variation from day to day, quite comparable in fact, with the mean variation found in judgments of brightness equality, when there is no difference in color quality to confuse the judgment. There is, moreover, so far as we have applied the method, a comparatively small variation for different observers.

until the contrast-stimulus again just matches the measuring disc. Since the proportion of sectors has not been changed from that which was determined for the standard lamp, it can be assumed that the illumination of the contrast screen is again of the same value it was for the standard lamp at the given distance. The comparative luminosities of the two light

TABLE I

SHOWING A COMPARISON OF THE RESULTS OBTAINED BY THE CONTRAST AND EQUALITY OF BRIGHTNESS METHODS

Source of Colored Light ¹	Color	Distance of White Light Giving Equality of Illumination		Sensitivity or Amount of Change that Can Be Detected by				Precision or the Mean Deviation from the Average			
		Equality of Brightness Method	New Method	Equality of Brightness Method		New Method		Equality of Brightness Method		New Method	
		Cm.	Cm.	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)	Cm.	Percentage (Candle-power)
87 cp. 41 cm. distant from photometric screen	Red	66.1	66.6	2.0	5.6	0.5	1.3	1.1	3.2	0.20	0.55
	Blue-green	59.5	59.5	2.5	7.85	0.5	1.65	1.5	4.85	0.22	0.97
52 cp. 38 cm. distant from photometric screen	Red	82.2	82.2	2.1	5.0	0.5	1.1	1.1	2.5	0.20	0.41
	Blue-green	70.9	70.5	4.0	10.4	0.5	1.4	2.0	5.5	0.25	1.1
13 cp. 38 cm. distant from photometric screen	Red	160.6	160	3.0	3.7	0.5	0.65	1.6	1.9	0.23	0.3
	Blue-green	134.5	134.9	4.0	5.7	0.5	0.76	2.2	3.2	0.24	0.46

sources, thus, can be computed directly by the law of squares from distance readings on the photometer bar. The advantage of the method for color photometry is, as has already been pointed out, that in the judgment in case of both the standard and comparison lights, the surfaces, the brightness values of which are being compared, are both illuminated by the same light. The eye is thus never compelled to make its judgment of two surfaces differing in color quality. The method is in fact almost if not quite as sensitive for the

¹ The colored lights were obtained in these experiments by means of the Wratten and Wainwright filters inserted in openings in the front of lamp-houses. The red filter used transmits the spectrum from $.768 \mu$ to $.65 \mu$; and the blue-green from $.52 \mu$ o $.465 \mu$.

photometry of lights differing in color quality as it is for the photometry of lights of the same color quality or for colorless light; and its sensitivity for lights of the same color quality or for colorless light compares very favorably, by test, for the same observer with photometers of the best Lummer-Brodhun type. The indirect vision judgment, it may be said, however, presents more difficulty to the unpractised observer than is afforded by the flicker judgment, but this difficulty yields rather readily to practice. The method has been in almost daily use in our laboratory for four years. It has, for example, been employed exclusively for the standardization of the illumination of our optics-room in the determination of color sensitivity.

Table I. has been prepared to show a sample of a comparison of the results of this method and the equality of brightness method. These results are typical. They report the average of twenty-five determinations. Sensitivity and the average deviation or precision are expressed both in divisions of the photometer bar and in percentage candle-power. The lamps used for this work were standardized by the New York Electrical Testing Laboratories. They were operated on a storage battery circuit.

With some modifications the contrast principle described above can be used for the determination in terms of pigment standards of the white-black value of colored papers for a given degree of illumination of the papers. The method of doing this can perhaps best be explained by comparing it with the method just described. In this method, it will be remembered, we determined how much contrast would be induced by one surface upon another of a lower coefficient of reflection when a given amount of light was incident upon the two surfaces, and used this amount of contrast as an index of the amount of light falling upon the two surfaces in establishing the photometric balance, or equality of illumination at the screen. Here the relation of coefficient of reflection of the screen to the stimulus is fixed and the amount of light falling on the screen from the comparison lamp is varied until the right amount is obtained to give the photometric balance with the

standard lamp. In the determination of the white-black value of a colored paper under a given illumination, the situation is a little different. The amount of light falling on the screen is kept constant and the relation to the screen of the pigment standard which is to express the white-black value of the color, must be varied until the right one is obtained. Here again we find out how much contrast is induced by one surface upon another of a lower reflection coefficient, in this case the colored paper; and this amount of contrast is taken as an index of the brightness relation of the colored paper to the surface of higher reflecting power, the screen *S* in Fig. 1, for the given intensity of illumination. The problem thus becomes to determine what gray sustains the same brightness relation to the screen *S* as does the colored paper. This gray should represent the white-black value of the color.

In detail the method is as follows: The stimulus-opening *O* is filled with the colored paper for which the determination is to be made and a disc of the same color is made a part of the measuring disc. The fixation is taken and black is added to the color on the measuring disc until it is sufficiently reduced in brightness to match the stimulus color darkened by contrast. The amount of black that has to be added becomes the index of the amount of contrast induced and therefore of the brightness difference between the screen *S* and the colored paper for the degree of illumination used, and is kept constant during the remainder of the work. In order to be able to find out what gray differs as much in brightness from the screen as does the colored paper, a disc made up of variable proportions of white and black is substituted for the colored stimulus behind the screen; and a sector made up of variable proportions of the same white and black, for the colored sector on the measuring disc. The white and black are then varied in proportions which are carefully kept equal for stimulus and sector until a match is obtained. When this match is gotten the relative amounts of white and black either in the stimulus disc or the substitute sector on the measuring disc should give the gray value of the color for the illumination employed. That is, there is obviously only one

gray that could be used in place of the contrast stimulus and in the substitute sector in the measuring disc which would satisfy the conditions of the experiment, and that is a gray having the luminosity or white-black value of the color originally used. It is scarcely necessary to caution that throughout the determination the light falling on the screen, the stimulus and the measuring disc must be kept constant. Care must be taken also in this case not to take the fixation so far from the stimulus-opening that a color difference is present between stimulus and measuring disc.

If the determinations are wanted in photometric units they can be gotten by the equality of brightness method from the grays which have been equated with the colors. A convenient instrument to use for this purpose is the Sharp-Millar portable photometer with its scale calibrated to give results in terms of candle-power per sq. in. The calibration can be readily made by the experimenter from a magnesium oxide surface with a known amount of light falling on it. If the light incident on the grays is daylight, the same difficulty will be experienced with the Sharp-Millar photometer, however, which was mentioned earlier in the paper, namely, the two halves of the photometer field will differ in color quality due to the fact that the carbon standard in this instrument gives a light rich in the long wave-lengths.

¹ In discussing the application of this method to the determination of the brightness of colored papers, reference should probably be given to the discussion of the Talbot-Plateau law in the paper preceding this. (See Ferree and Rand, 'A Preliminary Discussion of the Deficiencies of the Method of Flicker for the Photometry of Lights of Different Color,' *Psychol. Rev.*, 1915, 22, pp. 149-150.)

A SPECTROSCOPIC APPARATUS FOR THE INVESTIGATION OF THE COLOR SENSITIVITY OF THE RETINA, CENTRAL AND PERIPHERAL

BY C. E. FERREE AND GERTRUDE RAND

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The need has long been felt in physiological and psychological optics for better methods of specifying and standardizing the stimulus. In an adequate specification and standardization of the stimulus for work in these fields, three points are involved. Means must be had (1) of securing a small range of wave-lengths and of stimulating with them any part of the retina; (2) of determining accurately the values of the wave-lengths employed; and (3) of specifying the amounts of light used. In the present series of papers apparatus will be described with which it is, comparatively speaking, easily and conveniently possible (1) to stimulate any part of the retina with the light of the spectrum and to control as desired the conditions of preëxposure and surrounding field; (2) to control the amounts of light used within the small gradations needed for threshold and just noticeable difference determinations; and (3) to specify in C.G.S. units in any case in which it is wished the amount of light used. This work was begun and announced three years ago as the logical completion of work published at that time¹ and has

¹ See Rand, G., 'The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing,' *Psychol. Rev. Monog.*, 1913, 15, No. 1, 166 pp.; and Ferree, C. E., and Rand, G., 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Journ. of Psychol.*, 1912, XXIII., pp. 328-332.

If more time has been taken to accomplish what we have here to present than seems justifiable, we beg to point out that the work has been in many respects pioneer in character and that the difficulties on the radiometric side had not yet been overcome by the physicist at the time we began our work. We have also been greatly diverted by the pressure of other work.

The apparatus has been greatly simplified from its original construction. As it

involved the construction of a new type of campimeter, spectroscope, apparatus for the regulation of the amount of light used applicable to the spectroscope employed, and radiometric apparatus non-selective in its response to wavelength and sufficiently sensitive for the purpose in hand. The apparatus included under the first three of the above classes was constructed under direction by our department mechanician and should be within the technical capabilities of any good college mechanician. The description of this apparatus will form the subject matter of the present paper. For the radiometric apparatus we are indebted to Dr. W. W. Coblentz, radiometric specialist for the Bureau of Standards. Believing that the sensitivity of the thermopile could be increased by enlarging the area of the receiving surface and wanting to measure for at least one color all the light energy falling on the stimulus-opening in our campimeter screen rather than attempt to calculate it from one or more linear elements in this surface, we took up with Dr. Coblentz the feasibility of constructing surface thermopiles. He was asked to construct for us a surface thermopile having a receiving surface 16 mm. square, a trifle larger than the opening in our campimeter screen.¹ By means of this thermopile and one of the linear type we have been able to measure the light at three places—at the analyzing slit, at the campimeter opening, and at the eye. The use that is made of these measurements in the color investigation will be stated in a later paper.

DESCRIPTION OF APPARATUS

For the sake of convenience the apparatus may be described under three headings: (a) an apparatus for getting

now stands it is comparatively simple in form; it is not difficult to operate, and is, we believe, within the financial and technical possibilities of any laboratory in which serious work is being done in the optics of color. There is no work known to us in the investigation of color sensitivity in which light of a standard quality and intensity is needed to which this or a similar apparatus can not be adapted. On the spectroscopic side at least we hope it will prove sufficiently feasible and practicable to render undesirable the use of colored papers and filters in much of the work that is now being done in the optics of color.

¹ See Coblentz, W. W., 'Instruments and Methods Used in Radiometry'—II., *Bulletin of the Bureau of Standards*, 1912, IX., p. 22, ff.

the light stimulus of spectrum purity and of exposing different parts of the retina to this stimulus under any conditions of surrounding field, preëxposure, etc., that may be desired; (b) an apparatus for varying the intensity of the stimulus within the limits needed for threshold and j.n.d. work; and (c) an apparatus for measuring the intensity of the stimulus in terms of common or C.G.S. units.

I. An apparatus for getting a light stimulus of spectrum purity and of exposing the different parts of the retina to this stimulus under any conditions of surrounding field, preëxposure, etc., that may be desired.

To design an apparatus which will combine all the above features and which can besides be easily and conveniently operated is a task which has presented considerable difficulty.¹ Dreher² and Abney,³ for example, have each described apparatus devised to accomplish a part of what is outlined above, but the apparatus of neither would at all serve the purpose that has impelled us to take up anew the problem of the construction of apparatus.

¹ A statement of the points needed by an apparatus by means of which all the factors influencing the sensitivity of the retina to colored light may be controlled and which will have besides a wide range of serviceability is, in the belief of the writers, as follows. (1) It must provide an accurate means of separating out the desired ranges of wave-lengths throughout the spectrum. (2) Means must be provided for directing these wave-lengths to any part of the retina that is desired. (3) Provision must be had for controlling the brightness of the field surrounding the color and the brightness of the preëxposure. (4) The apparatus must be available for use in a light as well as in a dark room, else (a) the influence of the brightness of the surrounding field and of the preëxposure upon the response of the retina to the different colors can not be eliminated from the investigation when wanted; and (b) a large part of the work in the optics of color can not be done, namely, the investigations of response under different degrees of illumination. (5) A method of presenting the light to the eye must be had which will give the effect of a surface or field variable in shape and size that may be imaged on the retina. (6) The method of presentation must be such as to allow of no admixture of light from the room with the range of wave-lengths needed for the stimulus, and it must be as little as possible wasteful of light, else a sufficient range of intensity can not be had. (7) A beam of colored light should be provided of such intensity that its energy value per unit of cross section can be specified when desired at the point of entrance of the light into the eye.

² Dreher, E., 'Methodische Untersuchung der Farbentonänderungen homogener Lichter bei zunehmend indirektem Sehen und veränderter Intensität,' *Z. f. Sinnesphysiol.*, 1912, 46, pp. 1-82.

³ Abney, W. deW., 'The Sensitiveness of the Retina to Light and Color,' *Philos. Trans. of the Roy. Soc. of London*, 1897, Ser. A, 190, pp. 155-195.

A schematic representation of the apparatus under this heading is shown in the diagram in Fig. 1. It consists in

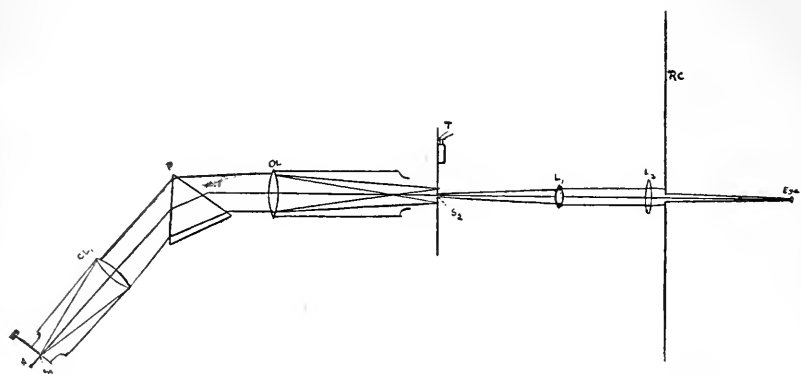


FIG. 1. Showing the Path of the Light from the Source to the Eye.

general of light source (*N*), spectroscope (*Sp*), micrometer slit (*S₂*) for separating out the wave-lengths needed for the colored stimulus, rotary campimeter (*RC*), collimating lens (*L₁*) for rendering parallel the beam of light emerging from the analyzing slit (*S₂*), and focusing lens (*L₂*) for bringing this beam to a focus on the pupil and for shifting the image formed to follow the pupil as the eye takes fixation at different degrees of excentricity.

It is scarcely needful to call to mind that one of the chief difficulties in devising a peripheral vision spectroscope has been to secure a means of throwing the colored light on the excentric portions of the retina. Dreher, for example, has tried to do this with limited success by holding the eye stationary and by reflecting the light to the different portions of the retina by a system of mirrors. By this means so much light is lost by reflection that the device would be useless for our purpose because we wish to be able to radiometer the light which finally reaches the eye. Moreover the difficulty in making the adjustments and the impossibility of making fine adjustments even for the different portions of the retina in the same meridian render the apparatus practically useless for extended work. Also the ordinary campimeter precautions with regard to the control of the brightness of the

surrounding field and preëxposure can not be taken nor can the apparatus be used in an illuminated room without the admixture of a great deal of light from the room with the wave-lengths selected for the stimulus. So far as we know, no attempt has yet been made to adapt the spectroscope to the campimeter, at least not in such a way that any meridian of the retina can be worked in easily and conveniently from center to periphery and an accurate control be had at every step of the brightness of the field surrounding the stimulus and the preëxposure.¹

¹ The hollow hemisphere, for example, used by Abney can scarcely be considered a campimeter for it was not designed for exercising any control over the brightness of the surrounding field. The apparatus was designed solely for dark-room work and was called by him a perimeter. The practical impossibility of uniformly controlling the brightness of the field surrounding the stimulus by means of an opaque campimeter screen hemispherical in shape was shown by one of the writers (Ferree) in a previous article. ('A Note on the Rotary Campimeter,' *Psych. Rev.*, 1913, 20, pp. 373-378.)

Abney describes two devices for exposing the peripheral retina to the light of the spectrum. Both are for use in the dark room. The first consists of a perimeter, the graduated arm of which is painted white, and the following auxiliary apparatus. Below the eye is placed "a small mirror on a ball and socket joint which by means of an arm causes a beam of light falling on it to be cast in any direction that is desired." The monochromatic light for the stimulus is gotten by means of an instrument which he calls his "color patch apparatus." The light passes from this apparatus to the mirror on the ball and socket joint which reflects it to the different points on the arm of the perimeter. In this way patches of color which serve as the stimuli for the eye in the color investigation are formed at different degrees of excentricity on the perimeter arm. That is, with regard to the method of securing the stimulation of the peripheral retina, this apparatus is of the usual type. The eye is held stationary and the retina is stimulated from center to periphery in a given direction by causing the colored stimulus to pass from the center to the periphery of the field of vision in the opposite direction. In his second apparatus, also called a perimeter by him, a hollow white hemisphere made of papier mâché is employed instead of a rotating arm. In the center of this surface is a circular aperture $1\frac{1}{2}$ in. in diameter to admit the stimulus light. To give the effect of a colored surface to this aperture when illuminated from behind with colored light, it was filled in with glass ground on both sides. In order that the shape and size of the stimulus may be varied, additional special apertures are provided which are placed as desired in the path of light immediately behind the fundamental aperture. As before, the color patch apparatus is used as the source of the stimulus light. The method of securing the excentric stimulation of the retina, however, is just the reverse of that described before. That is, the colored stimulus is kept in a fixed position and the eye follows a phosphorescent point which is moved from the center to the periphery of the hemisphere in the meridian in which the investigation is being made.

Neither of Abney's devices would have answered our purposes for the following reasons. (1) Neither is adapted for use in a light room. (2) Provisions for the

One of the difficulties encountered in attempting to do this is that when the eye is turned to take an excentric fixation, the pupil is rotated out of the beam of light. To overcome this, we have taken advantage of the simple fact that when the axis of a double convex lens is displaced from the axis of the beam of light, the image of the light is displaced in the same direction in which the lens is moved. Therefore, by moving the focusing lens (L_2) an appropriate amount in the direction the eye is moved in taking its excentric fixation, the beam of light can always be kept focused on the pupil, while no light energy is lost in the operation, at least not enough to be detected either by the eye or by the thermopiles, linear or surface, that we are now using. That is, in the apparatus shown in the diagram, the lens (L_2) which focuses the light on the eye, is mounted on a rack and pinion operating in the line of the fixation-arm of the campimeter. When a given meridian is to be investigated, the fixation-arm is turned into this meridian and the light is always kept focused on the pupil of the eye by means of fine changes in the position of the lens made possible by the rack and pinion adjustment.¹

control of surrounding field and preëxposure are lacking. And (3) the loss of light is so great and the method of presentation is such that the intensity of the light entering the eye could not be measured.

¹One of the objects in devising this means of presenting the stimulus light to the eye has been to get an apparatus that could be used in a well illuminated room, for only under these conditions, as has been shown in previous articles (see 'A Note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units,' *Amer. Jour. of Psychol.*, 1912, 23, pp. 331-332; 'The Effect of Changes in the General Illumination of the Retina upon its Sensitivity to Color,' *Psychol. Rev.*, 1912, 19, pp. 463-490; 'The Factors that Influence the Sensitivity of the Retina to Color; A Quantitative Study and Methods of Standardizing,' *Psychol. Rev. Monog.*, March, 1913, pp. 135-166) can the influence of the brightness of the surrounding field and of the preëxposure be eliminated from the investigation. Obviously a serious difficulty in working in an illuminated room is to get a method of presenting the stimulus to the eye that will give the effect of a colored field and prevent the admixture of light from the room with the wave-lengths which are needed for the investigation. The following methods may be used in dark-room work to get the effect of a colored field or surface to image on the retina. (1) Light of the desired range of wave-lengths is allowed to fall on a diffusely reflecting surface which is non-selective in reflection of wave-length. The standard reflecting surface for purposes of this kind is prepared from magnesium oxide deposited from the burning metal. Such a surface properly prepared has a high reflection coefficient approximately 90 per cent., and possesses

The Source of Light.—The requirements of a source for our purpose are (a) that it should give a light in which all the wave-lengths are represented in sufficient strength both for the needs of the investigation of color sensitivity and for radiometric standardization; and (b) that the light emitted shall be as constant as possible in intensity and spectro-radiometric composition. After trying many light sources we have finally adopted as best for our purpose the Nernst filament. This filament, after having been properly seasoned, the additional advantage that it can easily be kept fresh. And (2) light of the desired composition is allowed to fall on a diffusely transmitting surface also non-selective, or approximately so, in its transmission of wave-length. These methods of getting the effect of a colored surface or field while serviceable within limits for dark-room work, have the following objections for our purpose. (a) Both kinds of surface would reflect the white light of the room—the magnesium oxide surface, for example, would reflect approximately 90 per cent. of the light falling on it. This effect, however, is reduced to a minimum by using a double convex lens in the manner employed by us. For when a parallel beam of light falls on the lens and the eye is placed at the focus, the lens fills uniformly with light, and, so far as we are able to determine, white light is not reflected to the eye from the surface of the lens in appreciable amounts under the conditions obtaining in our work. That is, the lens is placed 2.5 cm. behind the stimulus-opening and the whole spectroscope and lens system are enclosed up to the campimeter screen in a light-tight compartment. Under these conditions by exercising a little care in the selection of the position of the apparatus with reference to the distribution of light in the room, so little light is reflected from the lens to the eye that the presence of the lens can not be detected when the eye is in position before the stimulus-opening and no colored light is coming from the spectroscope. In other words, not enough white light is reflected from the lens to render it visible to the eye. (b) Both of these methods are very wasteful of light. That is, there is not only a comparatively high percentage of absorption of light by the types of diffusing media, but only a small percentage of the light coming from any point or unit of the surface of these media enters the pupil of the eye. Thus there is not the possibility of getting the wide range of intensities of light needed to give the apparatus maximum serviceability for the investigation of color sensitivity. Furthermore, we are desirous of being able to specify in radiometric units the amount of light per unit area in the cross section of the beam of stimulus light at its entrance into the eye. This would be a very difficult task indeed with either of the two methods of presenting the stimulus light to the eye mentioned above. Its accomplishment, however, is not at all difficult by the method we have adopted. That is, instead of the light spreading from the stimulus-opening as if emanating from a source, it is concentrated into an image on the pupil of the eye, an image in this case of the analyzing slit. (S₂, see pp. 250, 261 and Figs. 2 and 3.) The amount of energy concentrated into this image can easily be determined by direct measurement with our radiometric apparatus for any of the wave-lengths used by us as stimuli, and the amount per unit area be estimated; further, if an artificial pupil were used, or the substitute to be described in a later paper, see *Psychological Review*, 1916, September number, the total amount of light entering the eye could be determined in C.G.S. units.

gives a light which changes comparatively little through long intervals of time. It has the advantage, moreover, that its shape well adapts it for use with the slit of the spectroscope, *i. e.*, the shape is such as to make it possible to utilize for the illumination of the face of the prism a relatively large proportion of the light emitted. Also by increasing the length of the filament and collimator slit, it is possible to increase in direct ratio the amount of light falling on the face of the prism. When in use, in order that no light shall be lost in passing through one or more condensing lenses, the filament

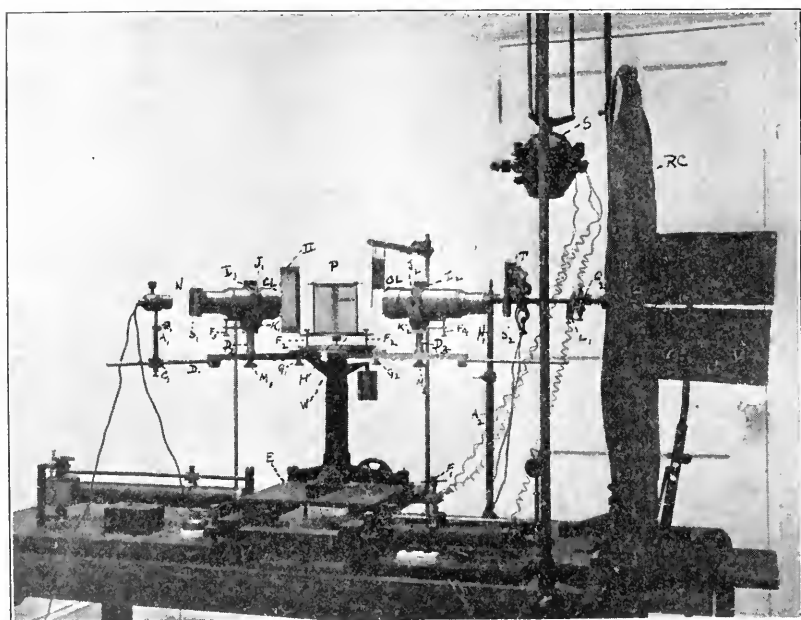


FIG. 2. Showing the Apparatus Grouped for Work—light source, spectroscope, thermopile, and rotary campimeter with its auxiliary lens system. In order that all stray light either from the general illumination of the room or by reflections from the Nernst glower be eliminated, the spectroscope and lens system are, when in use, enclosed from just in front of the Nernst to the campimeter screen in a light-tight compartment.

is mounted as closely as possible to the jaws of the slit. It is shown in position for work at (N) in Figs. 2 and 3. The filament is mounted in a lamp socket fastened to an upright

(A_1). In order that the height of the filament shall be adjustable this upright consists of a short rod sliding in a tube fitted with collar and set screw (B) which permits of a movement of the socket up and down, also to right and left. The upright (A_1) is fastened to the horizontal support (D_1) ex-

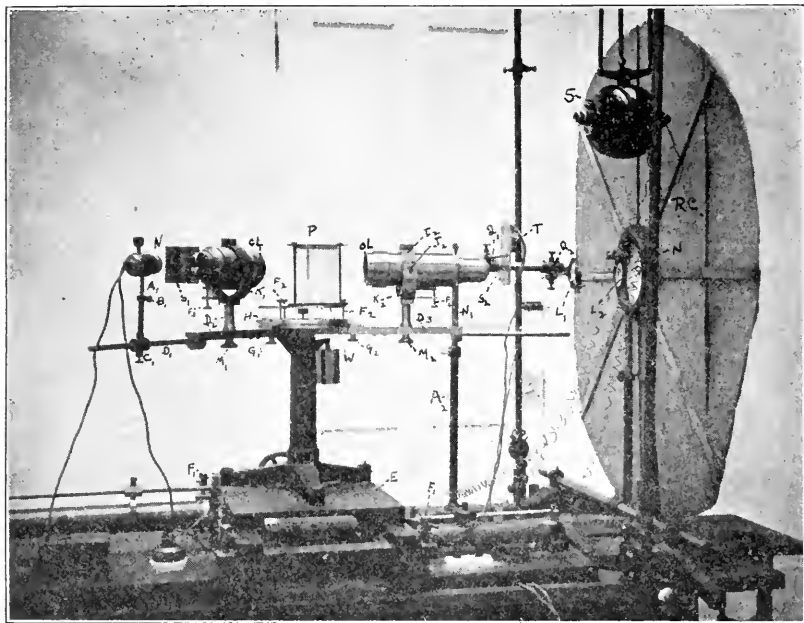


FIG. 3. Showing a Second View of the Apparatus Grouped for Work.

tending out from the collimator arm of the spectroscope by a clamp and set screw (C_1) which permits of the motion of the socket to right and left and to and from the collimator slit. The Nernst filament used by us is designed to be operated at 110 volts on a D.C. current, and has a carrying capacity rated at 1.2 amperes. When operated at its maximum capacity on a direct current, we have found, however, that the life of the filament is short. Satisfactory results have been obtained by us only when it is operated at or below 0.6 amperes. In series with the ballast, therefore, which is ordinarily used for the reduction of the current from the line and to compensate for the change in the resistance of the

Nernst material as its temperature varies, we have found it necessary to use additional resistance. This resistance is needed not only to cut down the current to the desired value, but to correct for fluctuations in the line. Two coils are employed, one coarse and one fine. The former is used to cut down the current to approximately the desired value, and the latter to correct for the fluctuations in the line. Both are in the form of adjustable rheostats. The second is of special construction to give the small changes needed. It consists of a cylindrical coil of wire wound on an insulated core of brass tubing and is operated by a screw motion in such a way as to give the effect of a slider on a single wire. This rheostat is described in greater detail on p. 275. It is not on the market but can readily be constructed to order by a laboratory mechanician. The finely graduated control afforded by it not only makes it possible to correct for fluctuations in the line, as is stated above, but also to compensate for the slow decrease in the carrying capacity of the Nernst material with use. The current consumed is measured by a Weston ammeter graduated to 0.02 amperes. Operated with this type of control the light flux obtained from the Nernst may be kept constant within the limit of change that can be detected either by the radiometer or the eye.

The Spectroscope.—In addition to the usual features attaching to a good spectroscope, our instrument was designed especially to meet the following needs. (1) To answer all the purposes for which a source of colored light may be used in the investigation of color sensitivity, a wide range of intensity is needed. In order too that an adequate radiometric standardization be made, it is especially desirable that light of high intensity be available. (2) If the spectroscope is to be used in conjunction with a campimeter, it is necessary that the objective arm remain in a fixed relation to the stimulus-opening of the campimeter screen and that some convenient and accurate means be had of changing the wave-lengths without changing the position of the objective. The first of these needs was met by employing a collimator slit long enough to admit the amount of light needed, and a

prism and lenses large enough to take care properly of the amount of light admitted. The second point has been met by us in the two following ways, one of which is technically more correct perhaps than the other. (a) The spectroscope was mounted on a stationary base supported by levelling screws. In fixed relation to this base a slit (S_2) was permanently mounted to separate out the wave-lengths which are to fall on the stimulus-opening in the campimeter screen. In order to be able to change the wave-length of the light falling on the slit (S_2) the stationary base carries a track along which the whole spectroscope may be shifted by very small amounts. This movement is made by means of a screw of fine thread turned by a wheel $4\frac{1}{2}$ inches in diameter. This track and the base of the spectroscope carry a Vernier scale graduated to $1/50$ of a mm. by means of which any previous setting may be accurately reproduced, and in terms of the readings of which the spectroscope may be calibrated in wave-length. This method of changing wave-length not only provides abundantly for small changes in wave-length but it obviates any necessity for readjustment of the collimator arm which would be the case were the wave-lengths changed, for example, by rotating the prism. In case the wave-length is changed by this device, the prism is set for minimum deviation for the D-line, and this adjustment is kept throughout. An adjustment which gives minimum deviation for the D-line alone is generally considered by spectroscopists to be adequate for the work in the visible spectrum when the light is passed through only one prism. Kayser, for example, says:¹ "Bei den Apparaten mit nur einem Prisma verzichtet man für gewöhnlich darauf, alle Wellenlängen unter dem Minimum zu beobachten, sondern stellt das Prisma fest auf, so dass etwa die D-Linien unter dem Minimum durchgehen. Die Dispersion ist bei einem Prisma so gering, dass dies gewöhnlich genügt. Das ist, aber nicht mehr der Fall, wenn man über die Grenzen des sichtbaren Spectrums hinausgeht, und so hat vielleicht zuerst Langley bei seiner Untersuchung des ultrarothten Theiles

¹ 'Handbuch der Spectroscopie,' Bd. I., p. 510.

tively the collimator and objective arms which are fastened to the stem of the spectroscope independent of the prism table; TD represents an arm fastened to the prism table in such a position as to be continuous with the radius of the table which bisects the refracting angle of the prism; AE and BE represent two rods of equal length which connect PA and PB at points equidistant from the center of the table to a collar which is free to play back and forth along the arm TD . M is a micrometer screw with a graduated cylindrical head, which is used to move the collimator arm through the small angles needed to give the change of wave-length. Opposed to this screw is a plunger p working against the spring in the case C . When the screw advances it moves the collimator arm forward and when it recedes the collimator arm is made to follow it by the push of the plunger p . The screw and plunger are supported by a curved arm coming off from the stem of the spectroscope, which can be clamped rigidly in any position which may be desired. This arm ends in two right-angled extensions, one of which carries the screw and the other the plunger. Between X and Y , the vertical arms of these extensions, the collimator arm is moved to give the change of wave-length. The micrometer screw passes through a fixed sleeve S graduated in fortieths of an inch. As the screw advances the cylindrical head telescopes on the sleeve S , one of the graduated spaces being traversed with each complete turn of the screw. The forward end of the cylindrical head is bevelled and on the circumference of the bevelled edge is a scale of equal divisions graduated in twenty-fifths of an inch. By means of this scale and the scale on the sleeve S , the advancement of the screw can be read in thousandths of an inch.

That minimum deviation is given automatically by this device to all the wave-lengths falling on the analyzing slit may be understood from the following considerations. In attaining minimum deviation the incident and emergent rays make equal angles with the normal to the refracting faces of the prism, therefore equal angles with the refracting faces themselves. When an adjustment is made for minimum

deviation for the D-line of the spectrum, for example, and the wave-length is changed by moving either the collimator or objective arms, the prism must be turned through half the angle through which the collimator or objective arm is moved if the wave-length traversing the axis of the objective tube is to be deviated the minimum amount. That is, for the prism to be set for minimum deviation the line bisecting the refracting angle of the prism will also bisect the angle made by the incident and emergent rays; hence if in changing the wave-length, the angle between the incident and emergent rays be changed a given amount by a movement of the collimator or objective arm, the prism must be moved through half that angle in order that the line which bisects its refracting angle will also bisect the angle made by the incident and emergent rays. The special purpose of the attachment described above, therefore, is to turn the prism through half the angle traversed by the collimator arm in changing the wave-length. This is attained by placing the prism on the table so that the radial arm *PD* bisects the refracting angle, and by connecting the moveable collar on the arm *PD* with the collimator and objective arms at points equidistant from the center of the prism table by rods of equal length (*AE* and *BE* of Fig. 4). Then when an adjustment is made for the D-line, and the collimator arm is moved through the angle needed to change the wave-length which falls on the analyzing slit, the arm (*PD*) turns through half that angle and takes up a position midway between the collimator and objective arms, and the part of the spectrum which falls on the analyzing slit is deviated the minimum amount in passing through the prism.¹

¹ A constant deviation prism may be used also for getting automatically minimum deviation for all parts of the spectrum. Such a prism may be constructed by setting two 30° prisms against the faces of a right-angled totally reflecting prism; or the prism may be made in one piece in such a way that the four vertical faces enclose four angles of 90°, 75°, 135°, and 60° respectively. In using this type of prism the collimator and objective tubes are set permanently at right-angles to each other. When this is done and the prism is rotated about a vertical axis, the different portions of the spectrum are thrown on to the analyzing slit and the portion that enters it at any moment, will traverse the system at minimum deviation.

In the early part of our work we used a constant deviation prism of the Cassie

Following is a description of the parts and mounting of the spectroscope. The collimator slit (S_1) is 12 mm. long. Its width is adjusted by means of a micrometer screw fitted with a head graduated to read thousandths of a mm. The collimator lens (CL) is a Zeiss triple achromat, 180 mm. focal length, 60 mm. diameter; the objective lens (OL) is also a Zeiss triple achromat, 240 mm. focal length, 60 mm. in diameter. The prism (P) is 100 mm. high and has a refracting base of 85 mm. and a refracting angle of 60° . Owing to the large size required, a liquid (CS_2) prism has thus far been used. With the exercise of a reasonable amount of caution to keep the CS_2 free from impurities, this prism has given very good satisfaction. At present we see no good reason why its use should not be continued. The analyzing slit (S_2) is made adjustable in length. The range attainable varies from 0 mm. to 12 mm. A slit adjustable in length is employed in order that the amount of light entering the eye may be made independent of the natural pupillary aperture. (See 'A Substitute for an Artificial Pupil,' *Psy. Review*, 1916, —, September number.) So far it has been mounted on an independent base screwed to the table in a fixed relation to the base of the spectroscope and the stimulus-opening in the campimeter. If desired this base might be made a continuation of the base of the spectroscope. In order that the distance of this slit from the objective lens (OL) may be adjusted for the different focal distances for the different wave-lengths, the frame in which the slit is mounted is furnished with a rack and pinion adjustment.

In Figs. 2 and 3 is shown the mounting of the spectroscope. At E may be seen the platform and track on which moves the carriage bearing the spectroscope. The platform is supported on four upright somewhat pointed screws (F_1) which serve the triple purpose of leveling the apparatus, of type which not only gives automatically minimum deviation but also the effect of a train of prisms; *i. e.*, the arrangement is such that the light is passed back and forth through the prism a number of times before it finally enters the objective tube. (Cassie, W., 'Multiple Transmission Fixed-arm Spectroscopes,' *Philos. Mag.*, 1902, Ser. 6, 3, 449-457.) This prism was constructed to special order of the dimensions needed for our apparatus.

allowing an adjustment of 4 inches in height, and of preventing chance shifting of the position of the apparatus on the table.¹ To this movable platform is securely fastened the heavy stem and tripod base on which the spectroscope is mounted. The prism table of the spectroscope is shown at *W*. It has two adjustments. (*a*) With its supporting table it can be rotated in the horizontal plane to provide for the adjustment of the collimator and objective systems at the angle of minimum deviation and to allow for change of wave-length by the rotation of the prism if that should be desired. And (*b*) it is furnished with three leveling screws (F_2) by means of which it can be accurately leveled. The collimator and objective tubes are mounted on two horizontal arms (D_2 and D_3) which rotate about the upright stem on specially prepared collars. D_2 furnishes the support for the light source and the collimator tube, and D_3 for the objective tube. In order that these arms when adjusted shall be

¹ In the construction of the carriage and track great care was taken that there should be no play or free motion of the parts. This was necessary in order that for a given reading of the Vernier scale on the carriage and platform the axis of the objective should always sustain the same relation to the slit (S_2)—in other words that for a given reading the same wave-lengths should always fall on the slit.

The calibration of this Vernier scale was accomplished by means of a Hilger direct vision spectrometer which has a scale reflected across the upper half of the spectrum. Since wave-lengths can not be read directly from this type of instrument, a supplementary chart must be made in which are given the values of the different scale divisions in terms of wave-length. This was done as follows. Twenty-six points in this scale were identified with the bright lines given by potassium, strontium and cadmium arcs and by the mercury tube. The wave-lengths of these bright lines were obtained from Hagenbach and Konen's 'Atlas of Emission Spectra,' and from these values the curve of wave-lengths was plotted for the entire spectrum. For the calibration of the Vernier scale the Hilger spectrometer was then mounted behind the stimulus-opening in the campimeter screen, and the wave-lengths coming through for any given reading of the Vernier scale were determined.

The calibration of the graduated scale on the fixed sleeve and cylinder head of the minimum deviation attachment (p. 258-260) may be accomplished in a similar way.

In case the minimum deviation attachment is used and the changes of wave-length are produced by it, such precision in the construction of the carriage and track as is described above is of course not necessary. That is, the carriage and track, while devised in our particular apparatus primarily for changing the wave-length, is very serviceable for other purposes which do not require such careful construction. For example, we have found this feature to be very useful in lining up the instrument with other apparatus, especially when the work requires the objective arm to be fixed as is needed in our adaptation of the spectroscope to the campimeter.

held rigidly in place, they are firmly clamped to the supporting table by means of the metal pieces (G_1 and G_2) one end of each of which is milled down to fit in a groove in this table (H) and the other is clamped respectively to the arms (D_2 and D_3). The collimator and objective lenses are each mounted in brass telescope tubing provided with a rack and pinion for the adjustment of its length. In order that the axes of these tubes may be in the same horizontal plane the following provisions for leveling are made. The tubes fitted about one-fourth of their length from the larger end with collars (I_1 and I_2), are swung on trunions (J_1 and J_2) in U-shaped housings (K_1 and K_2) supported by small vertical pillars coming up from the horizontal arms (D_2 and D_3). The smaller end of each tube rests on a leveling screw (F_3 and F_4) threaded in a short horizontal stem coming out from the housings (K_1 and K_2), by means of the adjustment of which the axis of the tube may be brought into the proper position. When this position is attained provisions are made for clamping the tube firmly in place. In order that room may be allowed between the prism and the collimator and objective tubes for the introduction of apparatus for reducing the intensity of light or for any other purpose that may be desired, the vertical pillars carrying the tubes run in slots 10 cm. long cut in the horizontal arms (D_2 and D_3). When adjusted to the proper position the pillars are firmly clamped to the horizontal arms by means of the milled nuts (M_1 and M_2). The analyzing slit to separate out the wavelengths to be used for the colored stimulus is shown at S_2 . The length of this slit may be made to vary from 0 mm. to 12 mm. Its width is adjustable by means of a micrometer screw fitted with a head graduated to read to thousandths of a mm. This slit is mounted vertically in an oblong brass frame, 12 cm. long and 6.5 cm. broad, carrying on each side a groove. In this groove slides a narrow brass plate on which is mounted a linear thermopile (T) with its receiving surface facing in the direction of the slit through a circular opening in the plate. During the color observation the plate and thermopile are raised out of the path of the beam of light

and clamped. For the energy measurements they are lowered to the level of the slit. In order to focus the different wave-lengths of the spectrum on the analyzing slit, a micrometer adjustment is provided to regulate the distance from the objective lens. The frame for thermopile and slit and the micrometer attachment are carried by an upright (A_2) which is mounted to one side of the path of the beam of light on a heavy independent tripod base screwed to the table. In order that there may be an adjustment of height, the upright consists of a tube 34 cm. long fitted at its upper end with a collar and set screw into which slides a steel rod (N_1) 38 cm. in length. The micrometer adjustment consists of a tube 30 cm. long and 15 mm. in diameter along the axis of which runs a finely threaded screw fitted with a milled head. In this tube is a beveled slot 5 mm. wide and 22.5 cm. long exposing the threaded screw. Telescoping the tube are two sections of tubing of larger bore (Q_1 and Q_2), 4.5 cm. in length, to the inner surfaces of which are screwed threaded pieces which extend down into the slot and engage the micrometer screw. As the micrometer screw is turned, these tubular sections move slowly along the screw. They are each fitted with collar and set screw which hold the horizontal rods supporting respectively the framework for the thermopile and the holder for the collimating lens (L_1). The collimating lens (L_1) is inserted in the path of the beam of light in order that the light emerging from the analyzing slit (S_2) may enter parallel the focusing lens (L_2) in front of the stimulus-opening in the campimeter screen. This lens has a diameter of 40 mm. and a focal length of 140 mm. Obviously if it is to act as a collimator for all the waves of light emerging from the slit (S_2), its distance from the slit must always be kept equal to its focal length. That is, when the distance of the slit from the objective lens is changed to accommodate for the difference in focus for the different wave-lengths of light, the distance of the lens (L_1) must also be changed by an equal amount and in the same direction. This is accomplished by the micrometer adjustment described above. That is, the tubular sections which carry respectively the framework

for the slit and the holder for the lens are both operated by the same micrometer screw, hence any movement of the slit is accompanied by a similar movement of the lens. An adjustment of the distance of the lens for the slit, once made, need not, therefore, ever be disturbed in the process of accommodating for the difference in focus for the different wave-lengths of the spectrum.

In order that all stray light either from the general illumination of the room or by reflections from the Nernst glower be eliminated, the spectroscope and lens system are enclosed from just in front of the Nernst to the campimeter screen in a light-tight compartment. So far we have found it most convenient to make this compartment of light-proofed fabric. That is, the compartment must be made large enough to enclose all of the auxiliary reduction and adjusting apparatus, the thermopile, etc., and must permit of easy entrance for the purpose of making the adjustments and settings required. The construction of a compartment having these requirements we found could be most simply and feasibly accomplished by employing, as stated above, light-proofed fabric. There are so many ways in which such a compartment can be constructed that space will not be taken here for a description of the compartment we have used. It will be sufficient to say that adequate care has been taken to exclude any stray light that might find its way into the stimulus by means of reflections and refractions within the system.

It is well known to spectroscopists that if some portion of the spectrum obtained by a single spectroscope be examined by a second instrument of good resolving power, frequently more than one band will be obtained. For example, if a spectroscope is so adjusted that only a narrow region of the red falls on the objective slit and the light emerging from this slit is passed through a second spectroscope, it may be found that the second resolution gives one or more comparatively faint bands in some other part of the spectrum. In most cases where a good instrument is used this degree of impurity would probably not appreciably change either the radiometric or optical results. However, we have endeavored to

devise means whereby light of such a degree of purity may be obtained that the second resolution shows only the one band. Our first step in this direction was (a) to eliminate as far as possible all stray light and internal reflections. Stray light was eliminated by carefully light-proofing the housing of the apparatus. Also the base of the prism and every other surface which might either admit or reflect extraneous light into the path of the refracted beam was blacked. Some of the harmful sources of internal reflection were found to be the bounding surfaces of the objective lens, the prism faces and the analyzing slit, principally the surfaces of the lens.¹ For example, in looking into the forward end of the objective tube a number of small images of the spectrum can be seen graded in size and nearly in line but projected to different distances. These images show of course that light is being reflected back and forth in the optical system. The amount of this reflection can be lessened to a considerable extent by reducing the area (cutting out the edges) of the lens and prism surface exposed to the beam of light. However, since this method of reducing the amount of internal reflection lessens also the intensity of light, only a limited use was made of it. If care is not taken to prevent it, light from neighboring regions of the spectrum will also be reflected back into the objective tube from the surfaces on either side of the analyzing slit. These surfaces should, therefore, be very carefully blacked. Some good perhaps is accomplished by slanting them slightly so that the edges of the slit point in the direction from which the light is coming. The effect of this is to reflect out of the system all light but that which passes through the slit. The edges of the slit also require careful attention if reflections are to be avoided. The knife-edge should not be obtained by a steeply pitched bevel on either side. We have found that very satisfactory edges may be made from sections of Gillette razor blades. (b) A minimum deviation device was attached to our spectroscope (see pp. 258-260). This was found to add a great deal to the

¹ The surfaces of this lens being concave on the side opposite to which the light enters the lens tend to reflect the parallel waves toward the axis of the beam, and thus again to mix the light which had been resolved by the prism.

purity of the spectrum.¹ But (c) the simplest and most effective device proved to be the use of thin gelatine filters especially selected with reference to the bands that were to be eliminated. The use of these filters in fact is enough to give the desired purity even when no other precautions are taken. Moreover, we were able to select these filters so that there was so little absorption of the light that we wished to use as to be of no consequence for the purposes of our work. They were mounted in an especially constructed holder between the objective tube of the spectroscope and the analyzing slit. A similar result could be accomplished by using two spectroscopes in series.¹ But the expense and inconvenience of doing this make it undesirable in work of the type we are doing, more especially when the desired purity can be obtained by the simple means described above with probably a negligible reduction of the intensity of the useful light.

APPARATUS FOR VARYING THE INTENSITY OF THE STIMULUS LIGHT

In designing an apparatus which will be at all broadly serviceable in the investigation of color sensitivity, due

¹Our attention was called to the effect of the minimum deviation by the observation that when the prism was adjusted for minimum deviation for the D-line and the wave-length was changed by shifting the spectroscope by means of the driving screw shown in Fig. 2, the farther the D-line was from the analyzing-slit, the greater were the number of bands which appeared in the field when the light emerging from the slit was examined by means of a second spectroscope. Without the use of the gelatines or a second spectroscope, however, we have not been able to get rid entirely of the bands mentioned above.

¹It is obvious that an advantage is gained here for purity over and above the increase in resolving power given by two prisms. Increase in resolving power is usually gotten by using a train of prisms in a single spectroscope or a single prism through which the light is passed more than once. (The Cassie prism used earlier in our work is of this latter type, see this paper, footnote, p. 260.) But while increasing the resolving power increases the purity of the spectrum (Schuster, 'Theory of Optics,' p. 163 expresses the dependence of purity on resolving power by the formula $P = pR$, where P represents purity; R , resolving power; and p , a factor which is a function of the slit-width), the impurities caused by internal reflections are clearly of a kind that can never be eliminated entirely by an increase of the resolving power of the prism or train of prisms. This, so far as we know, can be done only in ways similar to those described above. The use of a second spectroscope, however, besides being much more expensive and more inconvenient to manipulate, causes a greater decrease

attention should be paid to adequate means of varying intensity. This has become of especial importance because of the growing recognition of the usefulness of the threshold and just noticeable difference determinations as the basis of comparative work. We have designed, therefore, apparatus to produce both gross and fine changes in the amount of light employed, more especially the small gradations

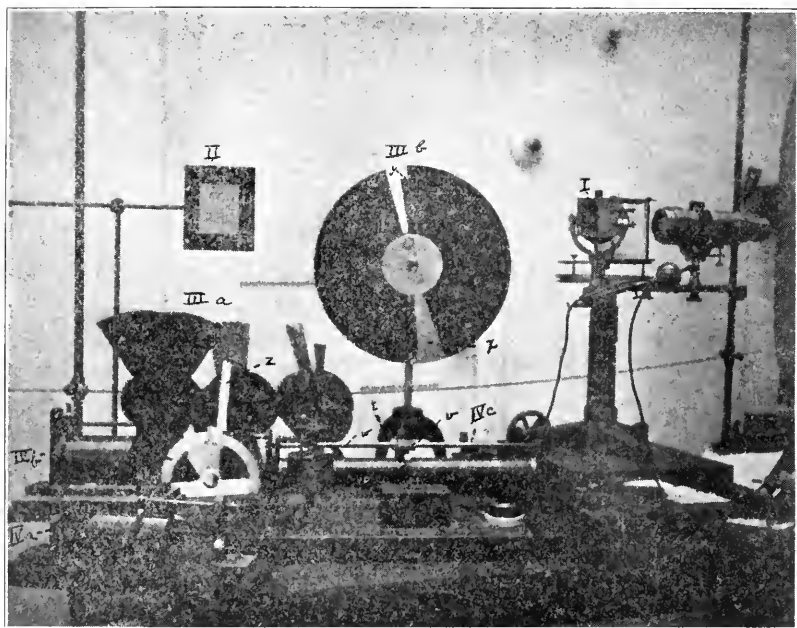


FIG. 5. Showing Auxiliary Apparatus Designed for the Reduction of the Intensity of Light—specially constructed resistance coils, coarse grating, aluminum sectored discs with Vernier protractor, and collimator slits including just noticeable difference slit.¹

needed for threshold and just noticeable difference determinations. This apparatus is shown in Fig. 5. It consists in the intensity of light used as stimulus than do the filters mentioned above, which when properly selected may produce practically no change in a given region of the spectrum and absorb heavily in other regions.

¹ In III. *b* the disc made up of a single 15° sector (*x*) is shown bright side before to make it distinguishable from the remainder of the compounded disc. When in use it is placed behind the other discs and the black side is turned towards the focusing lens just behind the stimulus-opening.

of (1) two types of collimator slit, one of which is especially devised for just noticeable difference work; (2) coarse gratings designed to give gross variations in the intensity of light; (3) sectorcd discs suitable for threshold and just noticeable difference work in which all of the changes from 0° – 348.75° total aperture may be made, and a protractor with Vernier scale to permit of close reading of the discs especially when the aperture is small; and (4) special resistance coils designed to vary the intensity of light at the source.

Collimator Slits.—One of these slits is of the usual type having carefully beveled knife-edged jaws 12 mm. long, with a micrometer adjustment of width graduated to thousandths of a mm. Such a slit may be used (a) to make a reduction of the spectrum as a whole or of any part, and the reduction may be computed directly from the slit width provided the source is uniformly luminous over the surface exposed; or (b) one part of the spectrum may be made in turn to sustain, within limits and under the conditions mentioned above, any ratio that may be desired to any other part of the spectrum, providing the original intensities from which the reductions are made, are known. This slit, however, is not adapted to just noticeable difference determinations for a given color or range of wave-lengths. The second slit (shown at I, Fig. 5) is especially designed for just noticeable difference work. This slit is constructed so that its upper and lower halves are independently variable in width. It was designed especially for some new methods we are using for a quantitative comparative determination of the retina's inertia to the different wave-lengths of light in which just noticeable differences are employed. In the short exposures used in tracing the sensation from the threshold to its maximum, it is obvious that the sectorcd disc could not be employed in making the variations needed for just noticeable differences. While designed to meet this special need we have found it to be a very convenient means of making the variations needed for much of the general work in just noticeable difference determinations. The slit is formed by three knife-edged jaws. That is, one jaw of the slit is made

in one piece and is 12 mm. long; the other jaw is made in two pieces, each 6 mm. long. One edge, the upper for the upper jaw and the lower for the lower jaw, is beveled to fit into a dovetailed guide cut in the frame. The other edge of each jaw is held in place by a slender close fitting key of appropriate length. The jaw, 12 mm. long, is stationary and the other two jaws are made to move away from it by two independent micrometer screws operated by drum heads graduated to thousandths of a millimeter. In operation the source is adjusted so that one edge of its equally luminous surface is flush with the stationary jaw and the other jaws are pulled away from it exposing as desired different widths of this surface. In a just noticeable difference series one half of the slit is held constant and the other is varied to give the just noticeable difference. When the width of slit needed for this is obtained, that half of the slit is held constant and the other is varied, and so on until the series is completed.

The Coarse Grating.—This device is serviceable for gross reductions of the spectrum as a whole. It is shown at II. in Figs. 5 and 2. The grating consists of an exposed photographic plate ruled on a dividing engine with lines 60 to the centimeter. The gelatine side of the plate is covered with a thin glass plate and the whole is mounted in a brass frame supported by a slender rod running parallel to the lines of the grating. This rod fits into a collar furnished with a set screw so that the grating may be rotated any amount that is desired about the axis of the rod. When interposed in the path of the light this grating allows the maximum amount of light to pass through when it is perpendicular to the path. As it is rotated, less and less light gets through the open spaces afforded by the lines, the amount depending upon the angle of rotation. If it were wanted to use this grating as a more precise instrument of reduction, it would be comparatively simple to add a graduated scale so that any previous setting might be reproduced, and to calibrate the scale so that the amount of reduction might be read directly from it. So far in our work we have not felt the need to do this as the grating has been used only in making gross reductions in the amount

of light employed, the finer changes being made either by the slit or by the sectored discs. This grating may be mounted anywhere in the path of the light from the source to the campimeter screen. Thus far we have found it most convenient to insert it between the collimator and the prism (see Fig. 2).

The Sectored Discs and Vernier Protractor.—Probably the most convenient and widely applicable apparatus for varying the intensity of light by known amounts is the sectored disc. A strong objection to the use of the sectored disc when fine changes are needed such as are required, for example, in threshold and just noticeable difference work, is the difficulty of getting and of measuring accurately sufficiently small amounts of change. Such discs are ordinarily constructed with two or more open sectors, and a change in one is multiplied as many times as there are open sectors. Moreover, an error made in the measurement of one sector is multiplied by the number of open sectors. This latter difficulty becomes especially significant in working with intensities at or near the threshold when a small error may represent a high percentage of the total open sector. We have sought to overcome these difficulties in two ways. (1) Our discs for a low total aperture are so constructed that one sector may be varied at a time. And (2) a special protractor has been designed fitted with a movable arm carrying a knife edge and Vernier scale graduated to read to $1/60$ of a degree.

Two sets of discs were made in all—one for simple reductions and threshold work, and the other for just noticeable difference determinations. The discs were cut from hard sheet aluminum No. 20 B. & S. gauge, 0.9 mm. thick; and are for the first set 19.5 cm. in radius. In order to give a wide range of change a number of discs are required. For example, a variation of total range of open sector from 0° – 348.75° is obtained in the first set of discs by using four pairs of two-sector discs and one pair of one-sector discs with a counter-balancing weight. In the first pair the breadth of each of the two open sectors is 90° , and the range of variation

of total open sector is from 0° – 180° ; in the second pair the breadth of each of the two sectors is 45° and the range of variation of total open aperture is from 180° – 270° ; in the third pair the breadth of each of the two open sectors is 22.5° and the range of total aperture is 270° – 315° ; in the fourth pair the breadth of each of the two sectors is 11.25° and the range of total aperture is 315° – 337.5° ; and in the fifth pair the breadth of the single sector is 11.25° and the range of total aperture is from 337.5° – 348.75° . In order that very small apertures may be obtained or that small variations of aperture may be had, when each open sector is 15° or less, a small single sector furnished with counterbalancing weight was provided in addition to the five pairs of discs. When this is used with the pair of discs having 90° sectors to cover one of the open sectors, the total aperture may be varied from 0° through 15° . This single sector may also be used in connection with any of the other pairs of discs to aid in making smaller variations in the total aperture than is obtainable with the pair of discs alone. That is, as one of the open sectors is opened, the other may be closed by any desired amount less than 15° by means of this single sector. Following this principle broader single sectors may be constructed to permit of smaller variations when the total aperture is still larger. We have found, however, that the 15° sector satisfies the need for the values of total aperture for which small changes are significant.¹

In order to make the first set of discs serve also for just noticeable difference determinations, it was necessary to supplement each of the pairs of discs in this set with single discs of the same breadth of sector and of lesser radius.

¹ In the construction of these discs a solid disc with a radius of 19.5 cm. was first cut from a sheet of aluminum. The open sectors were then cut into these discs of the breadth desired to a depth of 13.5 cm. This left a small solid disc of 6 cm. radius to support the pairs of sectors. As was stated above in order to guarantee symmetry of rotation in case of the single sectors, a counterbalancing weight was fastened on the opposite side from the sector 6 cm. from the center of rotation. This weight was in the form of a small lead disc soldered to the inside supporting disc in line with the radius which just bisects the sector. It is scarcely needful to say that great accuracy is demanded in the cutting of the discs. This accuracy was obtained by means of a special cutter designed for cutting with accuracy straight and curved edges in metal.

These discs were 17 cm. in radius and the open sectors were cut in from the outer edge to a depth of 11 cm. A margin of 2.5 cm. was thus left between the edges of the two sets of discs. In making the just noticeable difference determination the two sets of discs are adjusted so that the edge of the inner disc just bisects the stimulus-opening. The openings of the two sets are then varied independently as may be required, it being necessary of course always to make the open sectors of the outer discs the larger. The sectorized discs are shown at III. *a* in Fig. 5. The method of using them is further illustrated at III. *b*. Here the discs are shown mounted on an electric color mixer and are set for a just noticeable difference determination low in the intensity scale. Two of the set of larger discs each having two 90° sectors are mounted to give two open sectors one of which is closed by means of the single 15° sector shown at *x*, leaving a total aperture of 10° . In front of these is mounted the disc of smaller radius with the edge of one of its sectors shown at *y* projecting 4° into the 10° opening reducing it to 6° . When the disc so compounded is adjusted in front of the stimulus-opening so that the edge of the disc of shorter radius just bisects this opening and the disc is rotated at the fusion rate, the two halves of the opening are illuminated with light of intensities proportional respectively to 10 and 6. By using the discs of different breadths of sector, similar variations can be achieved over a range 0° – 347.75° open sector.

The special protractor by means of which the width of the open sectors may be read to $1/60$ of a degree is shown at *Z*. This protractor is provided with a 180° arc of 10 cm. inside radius, and an arm 27 cm. long which rotates about a central collar closely fitting the chuck of the motor. The 180° arc is graduated to $1/4$ degrees and the movable arm carries a Vernier scale graduated to $1/60$ degrees. The movable arm carries a beveled slot also of a 10 cm. radius of curvature into which the 180° arc fits. To insure accuracy of setting this movable arm is provided with finely beveled straight edges. When making a measurement of open sector, one of these edges is set flush with one of the edges of the sector

and the reading made. It is then rotated until the same edge is flush with the other edge of the sector, and the difference between the readings is taken as the value of the sector. We have thought it necessary to stress the accuracy with which these measurements must be made because the threshold value of sensation is frequently obtained for the intensities of light employed by us with a total aperture of $1/15^\circ$. With such small apertures it is obvious that accuracy of measurement becomes of prime importance. When used in connection with the spectroscopic apparatus described in a preceding section to determine the threshold and just noticeable differences in sensation, the sectorized discs are interposed in the path of the parallel beam of light just behind the lens L_2 (see Figs. 2 and 3). As is shown in this figure in order to eliminate as far as possible all vibrations and consequent displacements of the edges of the discs from the desired alignment with the beam of light, the discs are mounted on a motor (S) suspended by springs. With discs so designed and used, and with the proper standardization of the factors which influence the response of the eye, determinations may be made having a very high degree of reproducibility.

Special Resistance Coils.—Special resistance coils have been devised which serve the following purposes: (1) to give the fine changes of resistance needed to compensate for fluctuations of voltage in the lighting circuit which otherwise might produce troublesome variations in the flux of light from the Nernst filament; (2) to produce changes in the intensity of the spectrum given by the filament;¹ and (3) to make possible the fine changes in the speed of rotation of the discs that are so frequently required in work in the optics of color. These coils are of two general types. (*a*) Coils which give fine changes over a narrow range; and (*b*) coils which will permit of fine changes over a wide range. Coils of the first type are shown in Fig. 5 at IV. *a* and *b*; a coil of the second type at IV. *c*. The resistances of the first type consist of one coil and are constructed to give the effect of a

¹ It was recognized of course in using the resistance for this purpose that a change in the amount of current by which the Nernst is operated changes the spectro-radiometric composition of the light.

contact sliding along a single wire. The effect is produced by winding the coil of wire of the desired size and resistance on a hollow brass cylinder insulated with micanite, and by turning this coil by means of a screw motion under a U-shaped contact. In this way the contact is made to travel along the entire length of the wire, and the fineness of change is limited only by the size and coefficient of resistance of the wire. In one example of this general type of resistance shown in Fig. 5 (IV. *a*), the contact is kept stationary and the cylinder is mounted on a rod as its axis, threaded at both ends. As this rod operated by a milled head turns, the cylinder rotates and slowly advances, so that the contact travels continuously over the whole length of the wire. In a second example of this type, shown at IV. *b*, the contact slowly advances as the cylinder is rotated, and passes continuously over the whole length of the wire. This effect is accomplished as follows. The cylinder is mounted on a horizontal rod turned by a geared wheel 5 cm. in diameter. The contact is mounted on a threaded rod which is turned by a geared wheel of the same diameter as the wheel which turns the cylinder. As the latter wheel turns, its teeth engage the teeth of the wheel which rotates the rod on which the anchor piece of the contact is threaded, and the contact advances along the rod at a rate which keeps it continuously in touch with the wire throughout its whole length. The coil which we use to control the amount of current operating the Nernst filament is made of No. 26 wire, 47.8 ft. long, and has a resistance of 55 ohms.

The resistance of the second general type consists of two coils in series, one designed to make gross changes and one to add fine changes to it for any given setting of the contact. The wire of the first coil is wound on a long section of brass tubing insulated by micanite. This tube was given a stationary mounting and the changes in resistance are produced by a sliding contact shown at *v*. The supplementary coil was wound on a brass drum shown at *w*, insulated by micanite and mounted on a vertical threaded rod operated by a small wheel. As this wheel is turned the drum rotates and

slowly changes its level bringing every point on the wire successively in touch with a stationary contact. The connections are so made in this rheostat that by means of a double-pole switch shown at *t*, the poles of the large coil can be reversed and a high rate of speed can be instantly changed to a low rate of speed, and *vice versa*. In the rheostat shown in Fig. 5, the large coil is made of Advance wire No. 26, 139 ft. long, and has a resistance of 160 ohms. The small supplementary coil is made of wire of the same composition, No. 26, 17.4 ft. long, and has a resistance of 20 ohms. By means of these two coils changes of resistance amounting to very small fractions of an ohm can be made and the speed of rotation of motors of the type constructed by the C. H. Stoelting Co., for example, can be controlled to fractions of a revolution per second. We have found such control to be very useful in the general field of work in which impressions are to be given to the eye in succession, and especially necessary in the studies that we have made of the factors that influence the results obtained by the method of flicker for the photometry of lights of different color. It is obvious that some such control must be had if the phenomena produced by changing the rate at which impressions are given to the eye are to be studied in satisfactory detail.

THE ROTARY CAMPIMETER

In a previous paper¹ a rotary campimeter was described especially devised for use with pigment papers. At that time it was stated that this apparatus had also been adapted for use with a spectroscope, and that a description of it would be given in a later paper. The apparatus we shall here describe has been in use, therefore, for three years and its feasibility has been tested for that length of time both in the research and drill work of the laboratory.

The object of the rotary campimeter is to add to the vertical campimeter the rotary features of the perimeter, and thus to allow investigation of every possible meridian of the retina

¹ C. E. Ferree, 'Description of a Rotary Campimeter,' *American Jour. of Psychol.*, 1912, 23, pp. 449-453.

with as much ease and precision as was possible with the old form of campimeter in the nasal meridian only, or at most in the nasal and temporal merid'ans. As designed for use with the spectroscope this apparatus consists of two parts with appropriate supports and accessories: camp meter screen and lens to focus the light on the pupil of the eye and to shift the image to follow the pupil as it takes an excentric fixation; and attachment to line up the eye with the stimulus-opening. The campimeter screen rotates on a brass collar around a circular support. The stimulus is exposed through an opening in the center of the campimeter screen. Behind this opening mounted in a smaller brass collar is the focusing lens (L_2). This lens is carried on a rack and pinion which moves its center back and forth along a line which passes through the center of the stimulus opening and which contains all the fixation points on the arm ($I-I'$).

Fig. 6 shows the skeleton apparatus. It consists of the following parts: supporting base, frame for campimeter screen,

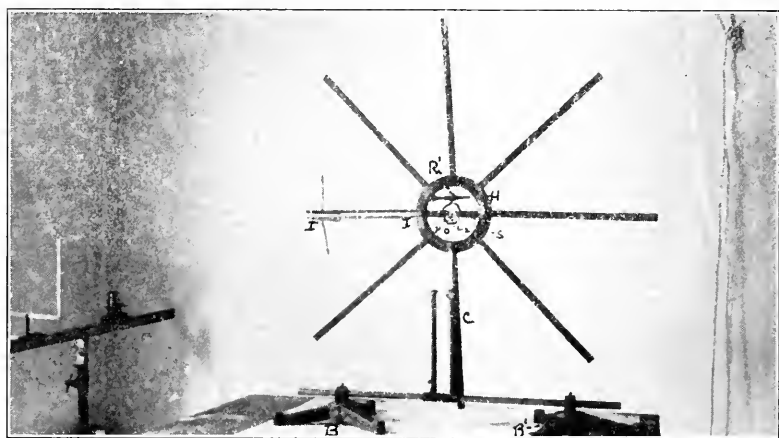


FIG. 6. Showing the Rotary Campimeter, the Lens for Focusing the Light on the Eye, and the Rack and Pinion used to shift the focal point as the eye changes its fixation.

rack and pinion adjustment and support for the focusing lens, and attachment for lining up the eye with the stimulus-opening. The supporting base consists of a horizontal steel

bar, 83 cm. long, supported by two tripod rests (B and B'). To this bar is clamped an upright (c) which serves as a support for the framework of the campimeter screen. In order that the distance of the upright of the screen above the table may be adjustable, this upright consists of a steel tube 27 cm. long and 15 cm. in diameter furnished at its upper end with a collar and set screw into which fits a rod 20 cm. long, to which the framework of the campimeter screen is attached. The framework of the campimeter screen consists of a stationary brass ring about which rotates a larger brass collar (H), 20 cm. in diameter.¹

The back circumference of collar (H) is graduated from 0° – 360° . To this collar are fastened the radiating arms. There are eight of these arms, one for each 45° mark on the graduated collar. They are made of steel and are 2 cm. broad and 40 cm. long. The eighth arm (I – I') differs from the other seven. It forms a right angle, one side of which lies in the plane of the background, and the other in front of this plane. The part in the plane of the background is 60 cm. long and the part at right angles to this plane is 28 cm. long. The arm is graduated from 18° – 57° along the section that lies in the plane of the background, and from 57° – 92° along the section at right angles. The graduations are based on the arc of a circle of 25 cm. radius. The rack and pinion adjustment (R') which carries the focusing lens is attached to the rotating collar. Thus when the arm carrying the fixation points is rotated into any given meridian, the rack and pinion adjustment is also rotated so that the line of motion of the center of the lens always contains the fixation points. The focusing lens (L_2) is a double convex lens 50

¹ This ring was made large in diameter for two reasons. (a) The ring had to be made thick in order to give sufficient rigidity to support the campimeter screen and to furnish the proper attachment for the rotary collar. Had the circumference been made small, the effect of the ring would have been that of a short tube. If the stimulus were viewed through a short tube, an induction factor would have been involved which would have been difficult if not impossible to standardize. The opening of the ring was, therefore, made considerably larger than any stimulus we wished to use in order to avoid the introduction of this factor. (b) The large circumference of the ring makes the apparatus available for investigating the effect upon sensitivity of varying the size of the stimulus.

mm. in diameter and with a focal length of 275 mm. It moves in a plane 2.5 cm. behind the stimulus-opening, hence the parallel rays of light entering it from the collimating lens (L_1) are brought to a focus on the pupil of the eye when in position 25 cm. behind the stimulus-opening. To the eye at this point, the lens, or as much of it as is visible through the stimulus-opening, is seen uniformly filled with light. That is, it is a well-known fact in physiological optics that when parallel rays of light are focused on the pupil of the eye, or more accurately perhaps, at the optic center of the refracting mechanism, by means of a double convex lens, the lens is seen by the eye as if uniformly filled with light. As the eye takes the different fixation points on the arm ($I-I'$) the light is kept focused on the pupil by slightly displacing by means of the rack and pinion adjustment the center of the lens in the direction in which the eye is turned in taking the new fixation.¹ The adjustment is quickly and easily made. In fact the rotary campimeter adapted to the spectroscope in the manner described in this paper presents little if any more difficulty of operation than it does when pigment papers are used as stimuli.

The device for lining up the eye with the stimulus-opening is also attached to the rotary collar (H) and is constructed as follows. A cross piece (S) 16 cm. long and 1.8 cm. wide is fastened by a screw with a milled head to one side of the collar (H) and is supported by a pin on the opposite side. A pin is used instead of a second fastening in order that the device may be conveniently and quickly turned out of the path of light when not in use. In the center of the cross piece (S) is a circular opening (O) 15 mm. wide. When in position immediately behind the opening in the campimeter screen which admits the stimulus light, the center of this opening lies in a line perpendicular to the opening in the screen at its central point. To the cross piece (S) 3 cm. to

¹ In taking a new fixation the pupil is seen to turn from under the colored image and to the observer the stimulus-opening is no longer filled with colored light. As the center of the lens is shifted in the appropriate direction, however, the image is seen to travel towards the pupil, and when it falls full upon it, the observer again sees the stimulus-opening filled with light.

the side of the opening (*O*) is fastened at right angles an arm 12 cm. long and 1 cm. wide, terminating in a disc (*P*) 2 cm. in diameter. Three centimeters from its outer end this arm is bent at right angles so that the disc lies directly behind the opening (*O*) and in a plane parallel to that opening. The size and position of the stimulus-opening, the opening (*O*), and the disc (*P*), and their distances from each other sustain such relations that when the eye is in position 25 cm. behind the stimulus-opening with the center of the image of that opening on the fovea and the line of regard normal to the plane of the opening, the edge of the opening (*O*) is just contained within the stimulus-opening and the edge of the disc is just contained within the opening *O*. That is, in effect the device is a peep sight arrangement, and the alignment described above is possible only when the eye is at the center of curvature from which the fixation points on the arm (*I-I'*) are determined. As stated above, this attachment is fastened to the collar (*H*) by means of a screw with a milled head, so that after the alignment is made it can be readily turned out of the road and clamped. In order that the distance of the eye may be adjusted at the same time as its alignment is made with the stimulus-opening, a measuring device 25 cm. long is provided. This device consists of a slender brass rod fitted at either end with two short right angled arms 5 mm. in length. On the end of one of these arms is a ring which is just larger than the stimulus-opening, and on the other is a brass disc of the same diameter as the ring, provided at its center with a pupillary aperture. In adjusting the distance of the eye the disc is rested lightly against the forward surface of the eyeball and the ring against the campimeter screen concentric with the stimulus-opening. When the position of the eye is once determined, a mouthboard is adjusted and clamped in position so that the observer's teeth fit into impressions previously made and hardened in wax. This fixes the relation of the observer's eye to the campimeter system. All that is needed, therefore, at subsequent sittings to bring the eye into this relation is again to fit the teeth into the impressions on the mouthboard.

In order to facilitate excentric fixation in the nasal and temporal meridians, the head should be turned in adjusting the mouthboard 45° nasalwards or temporalwards as the case may be. With the head so placed, the eye can swing easily from the stimulus-opening to a fixation point whose excentricity exceeds 90° .

The front view of the campimeter in readiness for use may be seen in Fig. 2 of our former paper; a back view is given in Fig. 3 of this paper. A cardboard background has been fastened to the steel arms by means of metal fasteners pushed through holes in the steel arms and clinched. Since the background is fastened to the arms attached to the brass collar (*H*), a circular gap is left at its center. This gap is filled by a disc (*N*) shown in Fig. 3, which has been fastened to the arms just outside of the collar (*H*). The disc is 27 cm. in diameter and contains the stimulus-opening (*O*), the size of which may be varied to accord with the purpose of the investigation. In order to complete the graduations on the fixation arm to the stimulus-opening, disc (*N*) is graduated from 0° – 18° . A background, 40 cm. in height, is fastened to the extension arms (*I'*). This background for screen and extension arm may be covered with whatever standard paper or surface that is desired.¹ The graduations from 0° – 92° are pricked in this covering at points determined by the markings on the back of the disc (*N*) and the arm (*I*–*I'*). These constitute the fixation points.

The method of using this apparatus is as follows. The eye of the observer is lined up with the stimulus-opening by means of the attachment described above at a point 25 cm. from the campimeter screen; and the position of his mouthboard is adjusted. With his eye in this position the lens should fill uniformly with light whenever the image of the analyzing slit falls on the pupil. Before the color observations are begun this is tested out by taking a number of

¹ In all tests of the relative and absolute sensitivity of the retina this screen should be made of a gray of the brightness of the color to be used. No departure from this rule should be permitted in tests of sensitivity unless it is for the purpose of determining the effect of different screens on sensitivity, or of using this effect as a means of varying sensitivity.

fixation points from 0° to the periphery of the field of vision and adjusting the focusing lens in each case to bring the image of the slit full upon the pupil of the eye. In making the color observation the unused eye is covered with a bandage. The arm ($I-I'$) is turned into the meridian to be investigated, the position being determined by the graduations on the collar (H). The experimenter inserts a card which we shall call the preëxposure card, between the eye and the stimulus-opening as near to the opening as possible while the observer takes the fixation required. In all investigations of relative and absolute sensitivity, this card should be made of a gray of the brightness of the color to be used. At a signal given by the observer the preëxposure card is withdrawn, the eye is exposed to the stimulus for the required length of time and the card is replaced in the path of the stimulus light. The observer is required to rest the eye after each observation. Further provisions against fatigue are made by frequent and regular intervals of rest.

It is often desirable to have an equation representing what is sensed at a given point in the peripheral retina in terms of what is sensed in the central retina. In this way a representation may be had for comparative purposes of the color tone, brightness and saturation for light of a given intensity and range of wave-length.¹ In the campimeter devised for use with pigment papers provisions were made for this. That is, it was possible to rotate a small disc on which the representation might be made, just behind the fixation point for all positions of the point from 0° – 90° in any meridian. This disc was rotated by a small motor the shank of which protruded through a slit 8 mm. wide running the full length of the fixation arm ($I-I'$). For a further description of this motor, its supports, adjustments, etc., and the method of making the match of the sensations aroused in central and peripheral retina, see the former

¹ In making a comparative study of the sensitivity of the different parts of the retina, such an investigation is a valuable supplement to a survey of sensitivity made on the basis of threshold and just noticeable difference determinations. The two methods are needed in fact to give a complete representation of the sensitivity of the retina in its quantitative and qualitative aspects.

article, p. 452. In the rotary campimeter devised for use with the light of the spectrum no similar provision has as yet been made. The difficulties appending the attempt to get a spectrum light variable at will in intensity, color, and brightness which can be easily and conveniently presented to the eye at any point of any meridian of the field of vision are obvious at a glance. Dreher, for example,¹ was able to make a match of the sensations aroused at the center and periphery of the retina without very inconvenient changes in his apparatus for one point only in the peripheral retina. An attempt is being made to adapt our present apparatus so that this match can be accomplished conveniently for any point in the peripheral retina, but as yet nothing definite can be promised.

¹ Dreher, *loc. cit.*



